Tampere University

Mohammed Salman Azim

DESIGNING A UNIVERSAL GRIPPING SOLUTION FOR HANDLING PART VARIATIONS IN A ROBOT APPLICATION

Faculty of Engineering and Natural Sciences
Master of Science Thesis
April 2019

ABSTRACT

MOHAMMED SALMAN AZIM: Designing a universal gripping solution for handling part variations in a robot application
Tampere University
Master of Science Thesis, 56 pages
April 2019
Master's Degree Program in Automation Engineering
Major: Factory Automation & Industrial Informatics
Examiner: Assoc. Prof. Andrei Lobov, Prof. Jose Luis Martinez Lastra

Keywords: Robot, Work cell, Robotization, Robot Gripper, Universal Gripper, 3D printed Gripper

In recent years, the affordability of robots and the progress in collaborative robotics has been of great benefit to the manufacturing industries. Robots can do the repetitive, monotonous and eco-unfriendly tasks with human collaboration and can increase the efficiency and accuracy of the production in a great manner. This thesis discusses designing of a universal gripping solution for part variations. It also discusses various aspects of building a robot work cell for soldering of SMPS transformer coils.

The reader will gain insight on how to handle different sized and different shaped parts using the same robot gripper. The state-of-the-art industrial robot grippers and universal gripping systems are discussed. A methodology is presented to design a proper universal gripping solution for such case. This can be vital in minimizing production cycle time by avoiding the need for tool changing for factories handling large variations in product shapes and sizes. This type of implementation can save resource, time and cost by avoiding extra hardware thus keeping the maintenance requirements low and thus less downtime of the work cell.

Finally, significant part of this thesis solves a use case problem by designing a universal gripping system to handle part variation in a robot-based application. Furthermore, it concludes with the learning and achievements through the process and scope for future work to improve the efficiency of work cell.

PREFACE

The work conducted to complete this thesis has been very challenging and exciting at the same time. This work would not have been possible without the support and assistance of some people.

First, I would like to thank Professor Jose Luis Martinez Lastra for being the examiner of my thesis. My deepest gratitude to my supervisor Associate Professor Andrei Lobov for his continuous support and guidance. His feedbacks and inputs helped me to think and reshape my ideas to fulfill the objectives of this thesis. It was a learning and interesting journey to work under his supervision and I thank him for giving me this opportunity.

I would also like to thank my colleagues from the Digital Manufacturing group and the Mechanical Engineering and Industrial Systems (MEI) department. I would like to pay my gratitude to Professor Kari Koskinen and Jussi Aaltonen for providing support to use the lab facilities. Gratitude to my friend and colleague Sankeerth and Laxmi for helping me with 3D designing.

Finally, my obligatory acknowledgment to my family, my mother and my wife. Without their love and support, nothing would have been the same. They have helped me to grow through my thick and thin and motivated me to complete this task. Love and respect from the deepest point of my heart to you all.

Tampere, 06.04.2019

Mohammed Salman Azim

CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

CAGR	Capital Annual Growth Rate
EOAT	End of Arm Tooling
HMI	Human Machine Interface
IFR	International Federation of Robotics
SMPS	Switch Mode Power Supply
TUTRoboLab	Tampere University of Technology Robotics Laboratory

1. INTRODUCTION

In this chapter, the problem and the motivation for this work will be discussed. The problem that needs to be solved, the objectives of the thesis and the methodology will also be discussed.

1.1 Background

Humans have always tried to invent solutions that will ease their daily work from the beginning of time. Innovation of intelligent machines had been our obsession to save human labor and time. Machines now do the work that needed human hands not long ago. Essentially, we have entered in an era where this is a striking reality. We develop machines that can do our work with better perfection than we can. Robots are such machines, which are made by mimicking the basic human abilities. These are designed to walk, talk, grab, transport and run like us. Some even do complex movements, which exceeds anthropoid abilities. The purpose of robots has been limitless. Social robots, robot dogs, cars, humanoid robots, toy robots are some to name a few. In this research, the main emphasis will be on industrial robots.

Robots started appearing in the industry in the middle of the 20th century. As mentioned in Spinger's Handbook of Robotics [1], It was on 1961, when General Motors employed the first robot Unimate for industrial service in its car manufacturing plant. It was also stated that, American scientist George Devol invented it based on his patent *Programmed Article Transfer*. The main task of this robot was to transport die castings and weld them on the bodies of cars in the assembly line [2]. From that time, the shift of task started from human to robot for the eco-unfriendly tasks like welding, painting, gluing, soldering etc. Tasks, which are repetitive, eco-unfriendly, precise, tiring and monotonous to human, robots are there to solve it all.

In present time, not only automotive, but also food, packaging, machining, electronics and manufacturing industries have turned into robot-based production. According to the Loup Ventures studies [3], about 61% of the robots sold worldwide are for industrial applications. The study also suggests that, according to the International Federal of Robotics (IFR) data, the robotics market can grow to $73 B by 2025 of which $33 B will be of industrial robots alone. The Compound Annual Growth Rate (CAGR) reached 15.4% by 2016 and the estimated trend was upwards for the coming years [3]. The IFR also claims that [3], 253,748 industrial robots were sold worldwide in 2015 which is an enormous number. This data supports the fact that in coming days, robot will be working with human in the factories more often if not by now.

This chapter will present the problem description of the thesis, followed by thesis objectives, work description, methodology and thesis outline.

1.2 Problem Definition

Employing robots to do any specific task for automation of the process is called Robotization. As discussed above, it is not a new concept. With new technologies emerging at a regular interval, there comes new opportunities to develop new solutions.

Switch Mode Power Supply (SMPS) transformer coils are parts widely used in consumer electronics. There are variety of coils produced according to the need of their application. The coils vary in sizes and shapes and the pin configuration. Most of the coils have vertical pins while some of them have both vertical and horizontal pin configuration. Fig. 1 represents a type of SMPS transformer coil.

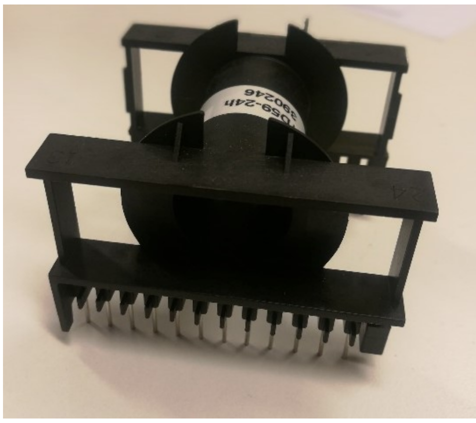


Figure 1. *Typical SMPS transformer coil*

The assembling of this coils undergoes several stages before they are market ready. In one of the stages, the coil formers are dipped in a bath of solder to join the copper windings with the pins on the bottom of the coil formers. Basically, soldering is a process used to join two metals using another liquid metal which is called the solder material. These materials typically have lower melting point than the metals that are joined. Therefore, when the solder is dried, it makes a solid bond between the two metals.

Usually, a human operator does this part of the assembly by hand. In the soldering station, the operator picks up the coil one by one, dips it in the hot tub of solder, and places them in a table after the solder is dried and fixed. The operator receives the parts in batches, transported from the winding section where copper wires are wounded on the core of the transformers. The point of interest of the company producing these parts, is to robotize the soldering process. Although the process may sound straightforward, there are many challenges to solve. Some of them are pointed below:

- The products produced vary largely in shape and sizes. The main problem is to design gripper/s to grip and hold all the variants to manipulate the parts.

- Designing a universal gripping solution, which will enable one gripper to handle all variants of transformer coils.
- Develop a work cell to integrate the whole task in a segregated environment by a cell with safety features.
- Integrate vision system for barcode read identification system for all types of coils and soldering quality control.

1.3 Objective

As described above, there are different tasks to solve for the completion of the project. As a part of this project, this thesis will cover the primary problems that needs to be solved to start the robotization process. Therefore, to be specific, the main objective of this thesis are as follows:

- To develop secure gripping system for all the parts for manipulation and completion of soldering operation.
- To develop a universal gripping system for all variants of parts, so that one gripper can handle all the parts.

1.4 Work Description

The major part of the thesis work, like designing and testing was conducted in TUTROBOLAB of Tampere University of Technology (TUT). The environment was set up with the required equipment in the initial phase of the project. Additional hardware and tools were introduced along the course of the project. Initially, a set of 53 SMPS transformers were delivered to TUT. These 53 transformer coils covered majority of the variants. These parts were used for the testing. Furthermore, upon request some copper wounded parts and an indexing station were delivered to TUT. See Chapter 2 for more on Indexing station. The environment in TUT was set up to mimic the actual production environment, so that, developed solution could be directly used upon completion on the original site.

1.5 Methodology

The method used during the whole implementation period from start until now is discover, learn and apply. In the initial phase of the project, the studies conducted are listed below:

- The provided 53 parts were studied thoroughly.

- The Robot that was selected by the members of this project and which is set up in TUT, was studied with some tutorials and basic operation was conducted.
- A readymade pneumatic robot gripper manufactured by German company Festo, modified by the company, was studied and tested. This gripper grips only a single type of coil from the 53 variants.
- State of the art robot grippers were studied.
- Universal gripping methodologies were studied.

After the above-mentioned studies, stages of designing, testing, failing and redesigning followed through the processes. Along the course, many other tools and techniques were studied and applied. Some of them are:

- Robot gripper controlling techniques
- 3D designing with SolidWorks
- 3D printing with different printers like Prusa, Prenta, Makerbot 3D printing machines
- Force measurement for grippers

1.6 Thesis Outline

There are six chapters in this thesis. The first one as discussed above is the Introduction to the thesis. It also sums up some background on the topic, objectives of this thesis and methodologies followed for the implementation. The second chapter covers the theoretical background and state of the art technologies used in the field of robotics, the structure of robot work cell and robot gripping methods. In chapter three, the approach to solve the problem is discussed. Chapter four includes the implementation of the different part of the work cell following the experiments conducted to achieve the objectives. The fifth chapter covers the results achieved through the final stage of implementation with some findings. The last chapter concludes this thesis and suggests possible future work in the related field.

2. STATE OF THE ART

In this chapter, basic structure of Robot work cell is discussed. The main elements of a robot work cell, like the Robot itself, input & output buffer and the robot gripper is also discussed. As the primary focus of this thesis involves universal gripping, the state of the art industrial robot grippers and universal robot gripping solutions are elaborated.

2.1 Robot Work Cell

A robot work cell is a cell where manufacturing or servicing work is conducted by means of one to many robots [4]. It is often included in a manufacturing industry for segregated production environment by restricting the process in a cage or cell. The separation is done for variety of reasons, the main ones being to increase productivity, flexibility, throughput and cost effectiveness [5]. Another reason for building a work cell is the safety of other workers and to prevent any kind of physical damage by the robot. The cell is designed in a way that the robot is caged in some solid material. The additional safety is arranged by means of sensors inside the cage.

Current research in human-robot collaboration has rendered a physical cage unnecessary, as the sensor technology embedded in the robot ensures everyone's safety. Bdiwi et al. [6] discusses four levels of interaction between human and robot in workspace. The first level states a non-shared workspace, and the cage can be of virtual means. The second level states a shared workspace with no shared tasks. Therefore, the robot cannot reach the human. In the third level, both have shared workspace and shared task with no physical contact. The contact might be only through handover of the work piece. The fourth level is the most advanced level where the human can guide the robot by physical contact. The modern-day collaborative robots can ensure the last level without any boundary between human in the workspace. These turn up a completely new domain and design criteria of a robot work cell. More on collaborative robots are discussed in section 2.2.

An eloquent design can make sure compact use of workspace in a manufacturing environment. In addition, the work cell may be isolated to limit the outside environment of harmful substances if the working environment deals with eco-unfriendly tasks. There is no universal design for a work cell and it may vary upon the application.

2.1.1 Structure of a Robot Work Cell

As mentioned earlier, there is no universal structure for a robot work cell. Still some basic things are present in every type of cell. The most basic and important components are as follows [4]:

- Robots
- Robot end effector
- Input buffer
- Task specific machineries
- Sensing equipment for safety
- Controller for controlling the cell
- Lighting
- Output buffer
- Protective barrier

The Robots are the center of all in a work cell. Here robots being industrial robots to be specific. More on Industrial robots are discussed in segment 2.2. The end effector of the robot is a significant part, which interacts with the working environment. In comparison with the human body, they easily correlate with hands. As a significant part of this literature, more on the robot end effectors are discussed in section 2.3.

The Input buffer acts as a feeder or supplier of parts to the robot. As the base of the robots are fixed except for mobile work cell, the parts need to travel to the reach of the robot for manipulation by some means. Whereas, the output buffer works as a delivery of finished products from the work cell. The buffer design can be of many types. Pneumatic actuators, hydraulic actuators, conveyor belts as well as some specialized fixed structures can work as an input or output buffer. Often the design criteria follow such that the input and output buffer can be maintained without disturbing the system. Therefore, there is always a flow of products through the work cell.

The controller for controlling the cell is another important element. Most of the time these are the teach pendant or Human Machine Interface (HMI) screen for controlling the robot. There are interlocked security arrangements, which ensures the safety of the environment. Interlocking is done by means sensing equipment, which can motivate the robot movement. Efficient work cell ensures the monitoring and controlling of the whole environment including the robot and the sensing equipment by the same controller. Finally, the protective barrier is placed to separate the cell from outside environment. The barrier can be of different materials like glass, steel cage etc. Classification of robot work cell can be of different types.

2.1.2 Types of Robot work cell

Depending on the robot positions, there are three types of robot work cell implementations [4], they are:

- Robot centered work cell
- In-line work cell
- Mobile work cell

Robot Centered work cell

Robot Centered work cell are the most common type of work cell. It may consist one to several robots based on application. The design criterion ensures the maximum use of the robot. The robot is based in the center of the cell surrounded by machines or task specific environment, input and output buffer. These types of cell are most common for small to medium sized production unit. Mostly machining, assembling, palletizing and packaging application employ this type of work cell. [4] Fig. 2 [4] illustrates the structure of a robot centered work cell.

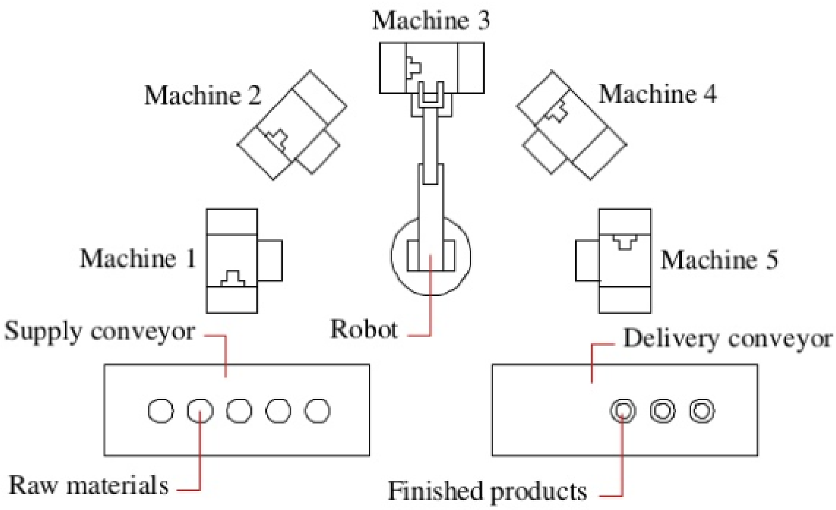


Figure 2. *Robot centered work cell* [4]

In-line work cell

Unlike robot-centered work cells, products rather than robots are at the center of this type of cell design. Single or multiple robots works on a single part or product while it passes through a line in the center. Usually the input and output buffer are same. Depending on the product supply type to the robot, this type of cell can be of two types. They can either continuous or intermittent transfer lines. Conveyor belts or moving rails are the most common types of feeder used in the in-line robot work cell. The most common application of this type of work cell are automotive industry. For welding, spray-painting and assembling cars, design of this type of work cell is common using the intermittent transfer type. This type of line also designed for consumer products packaging, sorting between multiple product items or quality checking where the line is rather continuous. [4] Fig. 3 [4] shows the basic diagram of an in line work cell.

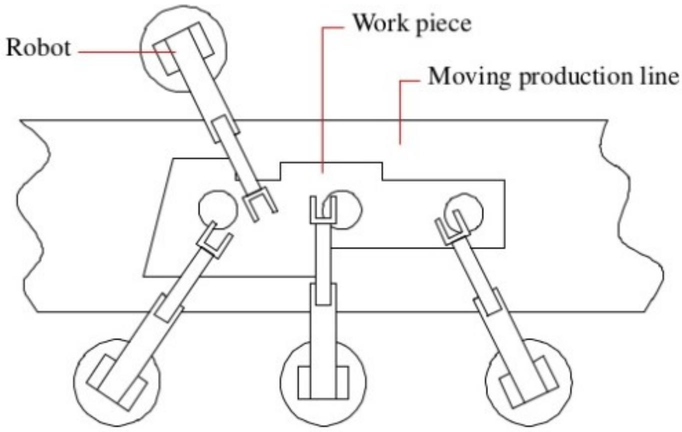


Figure 3. *In-line Robot work cell* [4]

Mobile work cell

Mobile work cell is the third kind in the list. As the name suggests, this type of cell provide movement of the robot in a specified area, usually in a linear motion, by means of rails. The robot base sits on top the rail and these bases include wheels for motion. The robot reaches the equipment or machines by moving along the rail. Depending on the rail position, this type of cell can be of two types. They are either floor mounted or overhead rail mounted work cell. In overhead work cell, the robot moves on top to reach the machines or parts. The most common type of implementation of this type of work cell is in warehouses, machining centers etc. [4] Fig. 4 & 5 [4] shows the two mobile work cell type structure.

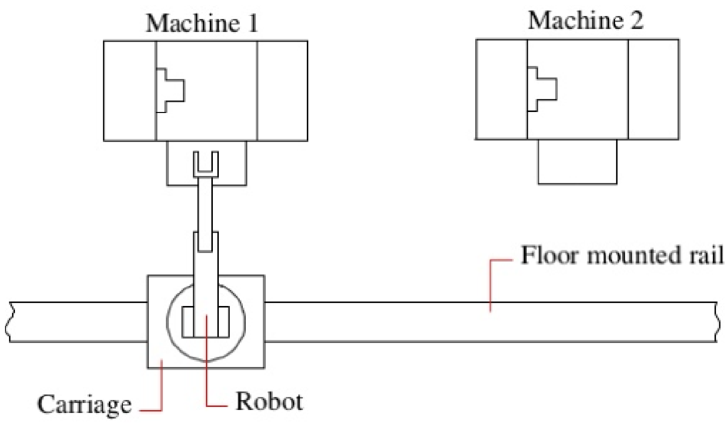


Figure 4. *Floor mounted mobile work cell* [4]

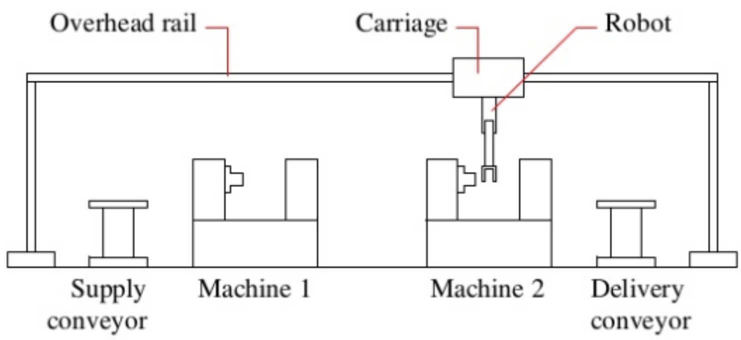


Figure 5. *Overhead rail mounted mobile work cell* [4]

2.2 Industrial Robot

As discussed earlier, the central element of a Robot work cell is the Robot, which covers most of the cost of a work cell. Unlike the movie industry's perception of robots, which usually depicts robots as humanoid features and capabilities, industrial robots are different. More often, the robots used in industries are called Robot manipulators. After joining hands with engineer and entrepreneur Joseph Engelberger, George Devol founded the first industrial robot company, Unimation [1]. These Unimation robots used a hydraulic control mechanism and the main applications of these robots were spot welding of car bodies and work piece handling [7]. This robot paved the way for an extensive new research field and opened the doors for automation in manufacturing industries, which became a norm in later years [8]. In 1973, the robot manufacturing company ASEA, which later became ABB, produced the first all-electric robot IRB-6, which used a microcomputer as a controller [9].

A robot manipulator is based of several joints and links. Joints facilitate the movement and links establish the connection between joints thus making the manipulator a single chain of moving body. The current industrial robots have generally 4 to 6 degrees of freedom (DOF). DOF means the possible axis the robot can move parts of its body. Over the years, with the need for different tasks, robot makers have manufactured different types of industrial robots, some of which are discussed below.

2.2.1 Cartesian Robot

Cartesian robots have linear motion on the X, Y and Z axis. They might have a rotational wrist but otherwise all the joints are prismatic. These types of robots are mostly used is machining and milling jobs. In addition, the overhead cranes in the factories use this Cartesian technique to move above the plant. Fig. 6 [6] represents the basic structure of a cartesian robot.

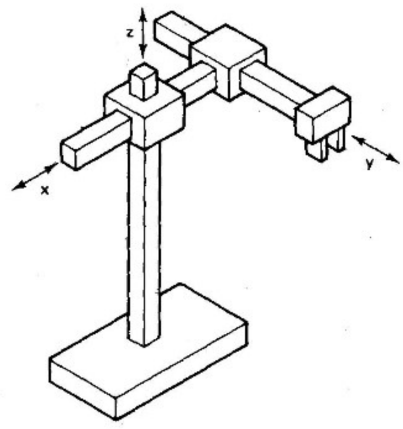


Figure 6. *Cartesian Robot* [6]

2.2.2 Cylindrical Robot

This type of robot typically has one revolute joint for moving in a cylindrical envelop. Usually the joint is the base joint and the base it attached to the ground. It also consists of prismatic joints for doing specific tasks. Fig. 7 [10] illustrates a basic skeleton of a cylindrical robot.

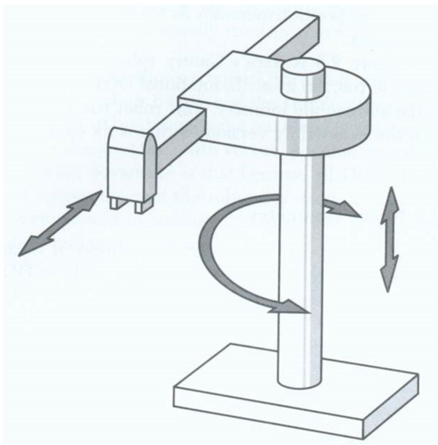


Figure 7. *Cylindrical Robot* [10]

2.2.3 Spherical Robot

Spherical robots consist of couple of rotational joints and one prismatic joint. These type of joint configuration makes it possible for them to work in a spherical envelop. Like cylindrical robots, the base of the robot is also attached to the ground. Fig. 8 [10] shows the structure of a spherical robot.

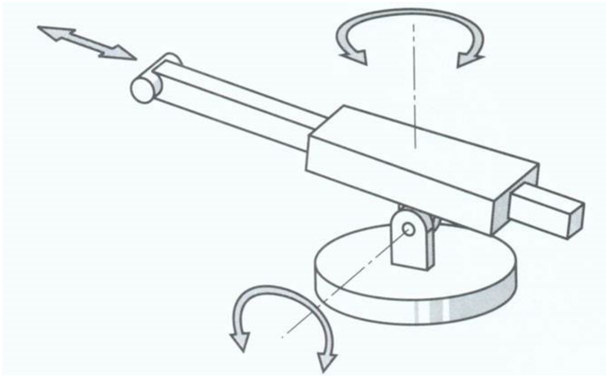


Figure 8. *Spherical Robot* [10]

2.2.4 SCARA Robot

SCARA robots became popular in the 1980s. SCARA stands for Selective Compliance Assembly Robot Arm. These types of robots usually have two rotational joints and one prismatic joint. The most common task this type is used in pick and place operations. The main field of SCARA robot is in electronics assembly lines for fast pick and place operations. Fig. 9 [7] represents the structure of a basic SCARA robot.

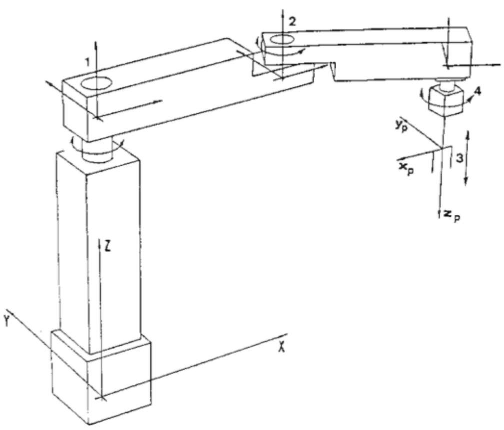


Figure 9. *SCARA Robot* [7]

2.2.5 Delta Robot

Delta robots are special types of robots having different architecture than a typical industrial robot. These robots have 3 degrees of freedom and have parallel kinematic configuration. The offering of this robot is fast operation and accuracy. For this trait, it is common to be found in high-speed pick and place operations. The base of the robot is typically upwards, and the robot operates upside down. Fig. 10 [8] shows a delta robot.

Figure 10. *Delta Robot* [8]

2.2.6 Articulated Robot

These type of robots falls in the anthropomorphic category. Having six or more degrees of freedom, these are the most flexible among all types discussed. It can reach a destination point in different orientations and offer high payload capacity. All the joints are typically revolute joints. Anthropomorphic robots are the most used robots and have variety of applications due to their offerings. Fig. 11 [9] represents the basic structure of an articulated robot.

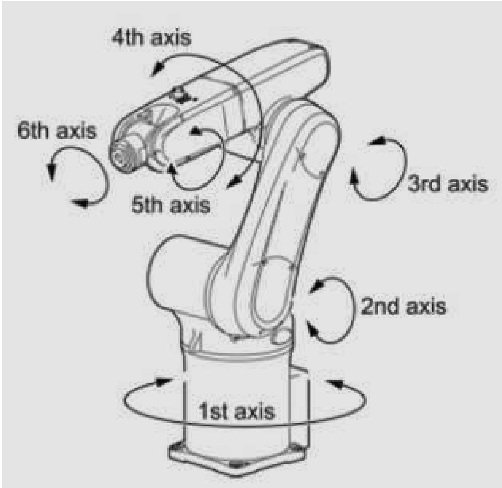


Figure 11. *Articulated Robot* [9]

2.3 Robot End Effector

End effector is the part of the robot, which interacts with the surrounding environment. Like human hands, robot needs some means of structure to manipulate objects. This end effector is typically connected to the end of robot wrist. Usually robots provide means to attach them at the end of the wrist. End effector may vary widely according to the task in hand. The main objective is to do the task accurately, safely and fast without doing any damage to the object.

In contrast to the human hands, which can manipulate objects by the use of fingers, robot end-effector design depends on the task heavily. For doing regular task, human use the movement of the finger. It needs certain skill to achieve expertise in doing tasks perfectly like making sculpture, pottery, woodwork, sewing, knitting etc. In case of robot, we can design the end effector for specific task and teach the skills by the controlling mechanism. Although the robots have been in the scene for quite some time, the need for a controllable and task specific end effector raised from the need in competitive manufacturing industries. It was in 1969, when a Mechanical Engineering student of Stanford University Victor Scheinman made the first fully controllable end effector also known as the "Stanford Arm" [11]. In the article, "Industrial Grippers: History and new innovation" [11], it was also stated that the previous Hydraulic Stanford arm was not controllable and dangerous. Following the Stanford arm, the research began to produce more controllable robot end effectors.

For handling objects safely, the control of the end effector needs to be accurate. This is the most challenging part of an end effector on which the success of the system is dependent. The most common form of task specific end effectors is welding torches, paint spray, soldering iron, glue gun attached at the end of the robot for welding, painting, soldering and gluing type of tasks. Regarding these, there are general-purpose end effectors also knows as robot grippers for grasping regular objects for manipulation. Bostelman and Falco [12] mentioned in their article that, an economical end effector, able to grasp objects with multiple shapes, weight, size and materials using a single grasping method are considered as grippers. As the application of this thesis is crucially centered on gripping parts for soldering, the discussion will cover only general-purpose grippers rather than task specific end effectors.

2.3.1 Robot Grippers

Robot grippers use the human-like finger mechanism for interaction with the object. It generally consists of two or three fingers with a single degree of freedom. The most popular ones are two finger grippers with parallel jaw movement. According to Jesse Hayes [11], the product manager of the renowned automation company Schunk Inc. in Morrisville, the parallel grippers are the most commonly sold grippers, making 60 to 70% of industrial robotics application. Although the number might be extensive, gripper makers still produce many other forms of grippers using different prehension technologies. From the control and design perspective, the gripper varies widely. Some of the main available grippers are discussed in the next section.

Pneumatic Gripper

Pneumatic grippers are controlled by compressed air. There are inlet and outlet valves through which compressed air passes, resulting a piston to move in two directions. Some external tool or jaws are connected with the piston through gears. Therefore, with the movement of the piston, the jaw or the tools move. These jaws can be of various forms and sizes. The placement of the jaws can be either angular or parallel. Parallel jaws give much wider stroke for gripping objects of wide range of sizes. The force applied by the jaws are dependent of the air pressure. The pressure then helps to hold the work piece in between the jaws. This type of grippers can be in one state, either open or close at a time. There are many applications of these types of grippers, especially where force or speed of the gripper is not an issue. Fig. 12 [13] illustrates some common pneumatic grippers in use currently.

Figure 12. *Various forms of Pneumatic grippers* [13].

Electrical Grippers

As the name indicates, the control of this type of gripper is done by electric means. There are usually servomotors, which drives the jaws of the gripper, which are controlled by electrical power. With this kind of gripper, force, speed and position can be controlled with some sensor involvement. In delicate applications, where force and speed control is of utmost importance, these grippers are widely used. It offers a great control and heavy payload. Fig. 13 [14] illustrates some common form of electric grippers.

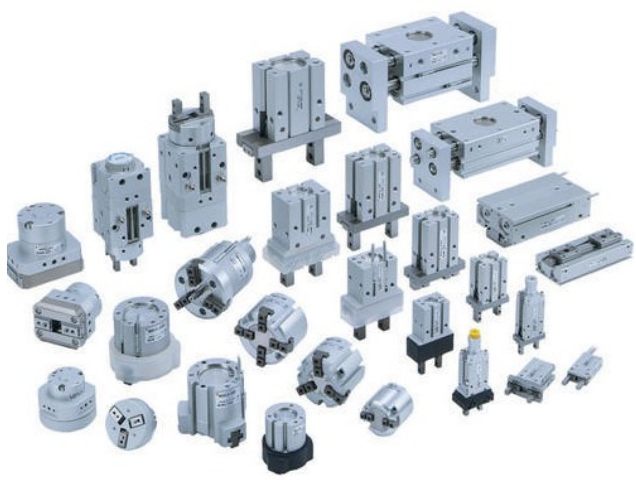


Figure 13. *Some common forms of Electric grippers* [14]

Magnetic Gripper

Magnetic grippers are controlled by electromagnetic means. Therefore, it needs also electrical power supply for magnetizing. Mainly, in picking up metal objects, magnetic grippers are suitable. It has also only two states where it can pick up an object by magnetizing and place the object by demagnetizing. Figure 14 [15] presents some common form of magnetic grippers.

Figure 14. *Common form of magnetic grippers* [15]

Vacuum Gripper

Vacuum grippers use suction cups to make contact with an object. They use compressed air to control the state of the gripper. These types of grippers are used widely in pick and place operations where variety of objects are involved. Figure 15 [16] presents some common form of vacuum type grippers.

Figure 15. *Common form of vacuum grippers* [16]

Adaptive Gripper

Modern day companies are bringing solutions that can solve multiple problems with one option. Adaptive type of grippers is such kind of grippers, which can grip objects of multiple shape. The specialty of this gripper is the intelligence. These grippers can change the gripping according to the shape of the object. Therefore, providing a whole range of options of work pieces to grip by a single gripper. Figure 16 [17][18] presents some latest adaptive grippers in the market.

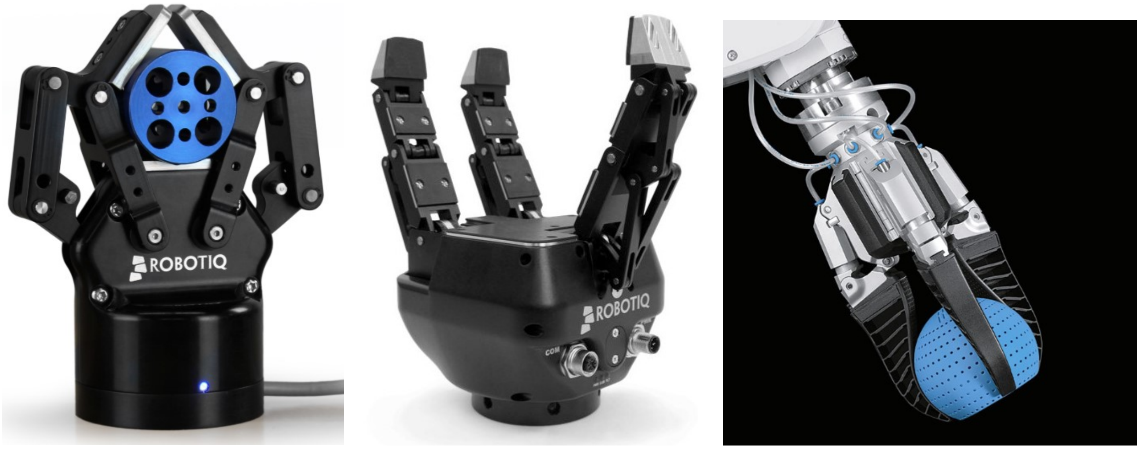


Figure 16. *Adaptive type grippers* [17][18]

2.4 State of the art of Gripping

In present day, as the robots become cheaper, accessible and universal, most of the research is carried out in gripping technologies. It is a human characteristic, which has led us to do many important tasks for ourselves. From picking up objects to lifting weight, making pottery to drawing pictures, all are human innovations, which are unique to the ability of other species. Robots lack the fluidic movement of humans but they surely can do other tasks, which are impossible for human, such as fast repetitive tasks with higher accuracy and lifting enormous weight. In a factory environment, grippers are used for logistics and manipulative purpose. Therefore, the grip is an important part in an application.

According to Kevin et al. [19], industrial grippers can be classified in two categories. One being the grippers for unknown environment and ones for the known environment. The unknown environment poses challenges for the gripper, as there could be variety of parts with different orientations. This type of challenges is met with means of different type of sensing system packed with the gripper. Vision system is the most advanced and feasible sensing technology in use today. Kelly et al. [20] developed the first vision based gripping system for picking cylindrical objects randomly oriented in a bin. Todays advanced camera systems and image-processing technologies makes it effortless to detect randomly oriented objects and grasp those with accuracy.

Speaking of grippers for known environments, the part orientation and position are fixed, and the robots are preprogrammed to reach those positions with the gripper oriented accordingly. According to the Machine design web resource [21], there are three basic type of grippers in use for these type of applications. Those are parallel grippers, three finger grippers and angled grippers. They state that major percentage of application are covered with these three variants. For safety and better accuracy, these types of grippers are now housed with different sensing devices such as force torque sensor, object detections sensor, tactile sensors etc. These three basic type of grippers are presented below.

Parallel Gripping

After the innovation of the first controllable gripper, the Stanford Arm, most of the later gripper followed the same model. It was a gripper with two parallel jaws. This design is still in use and the most common one. According to Jesse Hayes [22], the product manager of automation product supplier Schunk Inc. in Morrisville, N.C., 60 to 70 percent of robot application end up using parallel gripper. He also mentions the versatility of this type of gripper. The two jaws can grasp both cylindrical and rectangular objects. See Fig. 17 [23] for a common parallel gripper.

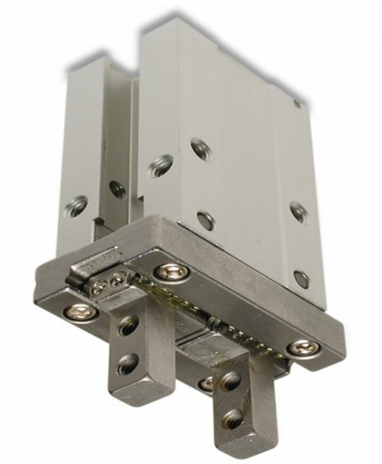


Figure 17. *Parallel Gripper* [23]

This type of gripper grasp objects by moving the jaws connected by mechanical attachments. It can grasp objects by applying force from both outside or inside of the object. Outside gripping incorporates closing the jaws and inside gripping by opening the jaws. Cylindrical shaped objects are grasped from the top and if the part needs an encompassing grip, then the fingers can be shaped according to the cylinder size. Most of the parallel grippers come with customizable finger attachment options.

Three Finger Gripping

Three finger grippers are second common type used in industrial applications. Crossly et al. developed one of the first three-fingered gripper in their article [24]. According to Jesse Hayes [21], it covers for 20 to 30 percent of industrial applications. Three finger grippers have three jaws placed in 120º angle to each other [21]. These grippers are specialized for griping cylindrical objects. The three jaws are connected with mechanical attachments and cannot move independently. These jaws can grip from inside of any part by opening until it reaches the body of the part. The outside grip holds any part by placing it in the center point of the gripper. Fig. 18 [25] illustrates basic three finger gripper.

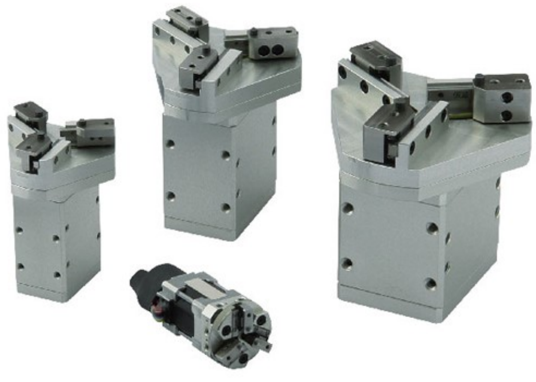


Figure 18. *Three finger grippers* [25]

Angular Gripping

Angular gripping has two jaws like parallel grippers, but the only distinction is the jaws open and close axially with a certain angle. These type of gripper make up for 10 to 20 percent of applications according to Hayes [21]. Operating in confined spaces where parallel grippers face problem wide opening, angled gripper makes it easier. This type of grippers can provide wide stroke ranges. Fig. 19 [26] illustrates basic angled gripper.

Figure 19. *Angled Gripper* [26]

All these three types of gripper are supplied with both electric and pneumatic power supply. Although the latter options are cheaper, but it needs extra equipment such as compressed air generator for operation. Electrical powered grippers are easy to operate and can be programmed externally with a computer.

Outside of the traditional categories, there are some unorthodox developments for special purposes both individually and from the companies. To mention a few, Festo's flexShape gripper motivated by the chameleon tongue [27] (see Fig. 20), universal gripper based on jamming granular material [28], Schmalz suction cup grippers with high temperature ratings [29] and various semi-professional 3D printed grippers are exciting developments.

Figure 20. *Festo FlexShape Gripper* [27]

2.5 Gripper Specifications

Gripper selection in a robot-based application is the most important and challenging task. The selection process might be time consuming if no proper knowledge about the gripper characteristics are known. There are numerous specifications listed for specific type of gripper. The application of this article considers the parallel or angular jaw grippers. Therefore, the specifications that needs attention for selecting a two finger or three-finger parallel jaw gripper are shortlisted and presented.

Stroke

Stroke of a gripper defines the distance travelled by the gripper jaws from minimum to maximum. It means the difference between the fully open and fully closed states of the jaws. The unit of stroke is millimeter (mm). This specification of a gripper can demonstrate the maximum gripping area of any product the gripper can reach. Usually the standard stroke provided varies between zero to several hundreds of millimeters.

Gripping Force

Gripping force stands for the pushing force applied while gripping any part. It is expressed in Newton (N). Gripping force is an important specification of a gripper. It ensures the stability of the product while gripped for safe handling. Too much pressure can damage the part and less pressure can result in drop of part thus affecting the operation and quality. According to a blog post by the gripper maker company Robotiq [30], the equation of force calculation for any product is:

$$F > \frac{m(g+a)}{\mu} * (safety\ factor) \qquad (1)$$

Here, F is the force [N], m is the mass of the product [Kg], g is the gravitational acceleration 9.81 ms^{-2}, a is the robot acceleration, μ is the coefficient of friction between the gripper finger and the work piece. The coefficient of friction is dependent on the product and finger material. Lastly comes the safety factor, which depends on the type of application and environment. The overall force will be the sum of all the gripping fingers.

Another gripper maker company SMC [31], states the force calculation equation in their product brochure as:

$$F = \frac{mg}{2 * \mu} * a \qquad (2)$$

Here, all the parameters are same as equation (1), except for a being the safety margin. From the equation, the condition under which the work piece will not drop is $F > mg/2*\mu$. Here, 2 stands for 2 finger grippers.

Gripping Speed

The gripping speed specifies how faster the gripper jaw opens or closes. It is important as it can affect the cycle time of any application. The unit of gripping speed is $mms^{-1.}$

Payload

Payload means the maximum amount of weight the gripper can carry. It is expressed in Kg. It is an important factor for application with high load requirements. The gripper weight and the robot's payload should also be considered while gripper selection. The robot's payload should be greater than the gripper's payload capacity.

Repeatability

Repeatability is the specification, which defines the gripper's position accuracy over a certain cycle period. This feature should be considered for applications with high accuracy requirements. The repeatability is expressed between 0 to 1 without any unit. The lower the number, the higher the accuracy.

2.6 State of the art of Universal Gripping

Over the years, many solutions have been developed for universal gripping. From those, some are invented by individual research and implementations, while some are readily available solutions in the market supplied by major automation supplier companies. However, with availability comes the cost. The solutions vary in price as well as in performance. Some solutions could be applied directly while other could be implemented with some in-house engineering. Pham & Yeo [32] surveyed and presented some strategies for universal gripping in their article. Some of those techniques with some modern additions are presented below.

2.6.1 Finger Dimensioning

Earlier it was stated the most common form of industrial grippers are basically three types, the parallel jaw, three finger and angular grippers. The first technique that can be applied to achieve universal gripping is the finger dimensioning method. Above-mentioned grippers come with default fingers or no fingers at all. Notching the fingers according to the need of the application can solve the gripping problem of multiple shaped objects. From studying the product in detail, the common gripping surfaces can be found. Those common surface patterns are then notched on the gripper fingers, although it limits the type of shapes that fingers can carry [32]. This type of gripping system can be applied if one gripper can fulfil the stroke, gripping force, parts weight and other important requirements by the product range. Some example are presented in the article [33].

This method is the cheapest option of all the methods. As only one gripper is used, the cost for multiple gripper is minimized. This method can essentially guarantee the lowest cycle time as the robot is always on production and no downtime for gripper changing. However, some design time is required to bring out the suitable gripping pattern for all shapes. Knowledge of 3D modeling is required. The model can be then manufactured by 3D printing or machining technology depending on the finger material.

2.6.2 Multiple Finger Gripper

The next method is the multiple finger gripper method where sets of fingers are used by a single gripper. One gripper is always attached with the robot and sets of fingers are made according to the products gripping surface. This technique can be used for wider range of parts as numerous finger sets can be made. However, all the products must fall under the same gripping attributes like the stroke and the force and so on to operate under same gripper.

The finger changing can happen automatically or manually. For automatic finger change, there must be some mechanical arrangement like screwing and unscrewing and the finger sets has to be within the reach of the robot. In manual changing, an operator can change the fingers by hand. As a result, the cycle time will increase. Comparing to the finger dimensioning method, the cycle time of both automatic and manual changing system will be greater. Fig. 21 [34] shows a manual gripper finger changing system.

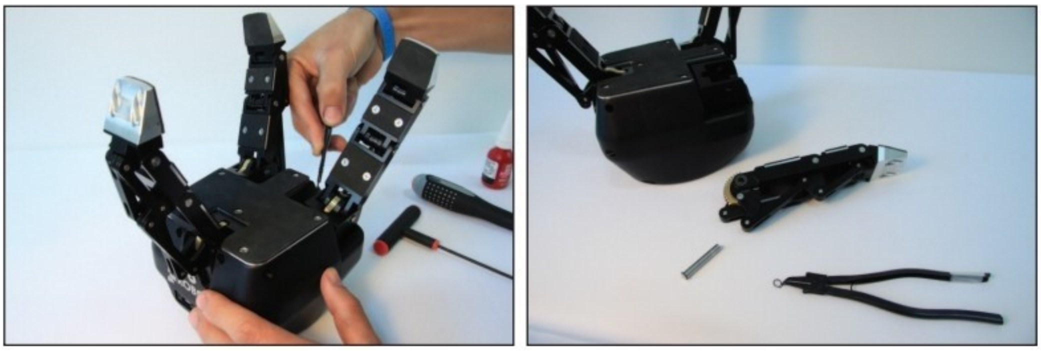


Figure 21. *Manual gripper finger changing* [34]

2.6.3 Multiple Gripper Solution

When a single gripper cannot handle the variety of parts, multiple gripper solution can be used. In this method, multiple grippers are placed in the work cell and those are changed according to the product in operation. A gripper changing station can be also built to place all the different grippers. This type of method can ensure the safe gripping of all types of parts.

Like the fingers, grippers can be also changed automatically or manually. This change is done by mean of a gripper changing disc. This is mechanical coupling attached with the robot and the other side with the gripper. There are two type of tool changers, automatic and manual. Automatic tool change is operated by electrical or pneumatic control. Fig. 22 [35] illustrates an automatic tool change system.

Figure 22. *Automatic tool change* [35]

The manual tool changer needs human hand every time the gripper needs to be changed. Therefore, the cycle time of this system is always higher than the automatic tool changer. The manual tool changer is presented in the below figure [36].

Figure 23. *Manual tool changer* [36]

In their article [37], Causey & Quinn suggested to avoid tool changing as it decreases the throughput of the system with respect to other system available. It also needs monitoring of the system for proper mounting of gripper every time there is a change.

2.6.4 Multiple Gripper Frame

Attaching multiple gripper at the same time with the robot is another useful universal gripping system. This can be done by attaching a multi gripper frame to the wrist of the robot and then mounting the grippers on the frame. This system offers lower cycle time then the previous system as there is no change of grippers and the robot can choose any gripper with only the wrist movement. Fig. 24 [38] presents an example of a multiple gripper frame attached to the robot.

Although it is beneficial to use multiple grippers at the same time for different type of gripping, it can essentially decrease the payload of the robot, as the grippers are always mounted on the robot. The 3D space around a single gripper also decreases because of the package.

Figure 24. *Multiple Gripper frame* [38]

2.6.5 End of Arm Tooling (EOAT)

Another technique for universal gripping used in the industry is the End of Arm Tooling (EOAT) method. Using this system, a frame carrying all the essential tools for the application is mounted on the robot. This type of system is applied when the need for different tool is greater than any other system can provide or there are numerous units of a gripper is needed to carry heavy loads. This type of system can be expensive and require designing for specific task. The overall payload of the system is decreased as the frame remains connected with the robot all the time. In Fig. 25 [39], an example of an EOAT tool is presented.

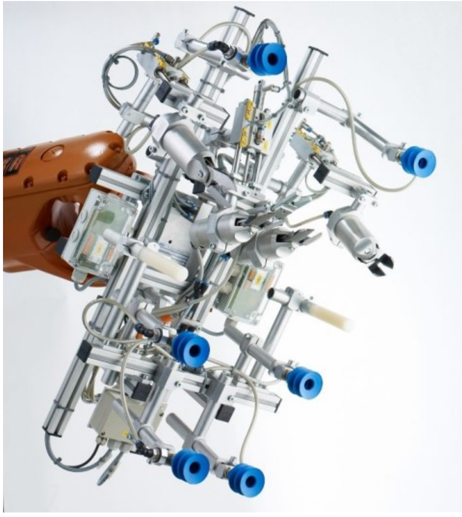


Figure 25. End of arm tooling [39]

2.6.6 Others

There have been many developments of different types of universal gripping solution, where the grippers are designed using a unique approach to grasp many objects with a single gripper. One of them is a gripper designed by jamming of granular material inside an elastic membrane [28]. This type of grippers is often called a passive universal gripper. A balloon, granular material like sand or coffee beans or other material and one pump is required in this design. The gripping and releasing occurs by applying pressure difference inside the elastic membrane. When the pump sucks the air, the gripper grips the object by adjusting to the shape of the object. With this kind of gripper, the gripper can grip objects of arbitrary shapes. Fig. 26 [28] shows the universal gripper holding to bottles of salt and pepper.

Figure 26. *Universal gripper holding two bottles at a time* [28]

But as Brown et. al. [28] discuss in their article the possible disadvantages of this kind of gripper. The repeatability of the gripper is less than typical industrial grippers. The elastic membrane can be damaged and the most important of all, the position and placement cannot be controlled. This type of solution can be good option for only pick and place type solution of random objects.

There are other universal grippers developed which are multi fingered grippers actuated by pneumatic means. These are also called soft grippers. As the name suggests, the fingers of these grippers are built with soft material to add the flexibility. This characteristic helps the gripper to grip multiple shaped objects. Fig. 27 [40] is an example of such kind of universal gripper.

Figure 27. *Multi-fingered soft universal gripper* [40]

Although the gripping range is appreciable with certain gripper types, still the reliability and the precision are considerable shortcomings.

2.7 Summary

In this chapter, a range of topics were covered. First, the basic structures of a robot work cell were discussed followed by important elements of the work cell. The main element, the industrial robots were discussed including the different types. Different types of robot grippers were studied and documented. The state of the art of robot gripping was also included. The selection of a gripper can be demanding, if knowledge of important gripper characteristics are unknown. Therefore, the considerable gripper specifications were also discussed in this chapter. As the main objective of this thesis relates to universal gripping, the state of the art universal gripping solutions with examples were covered.

3. APPROACH

This chapter will focus on the approach towards universal robot gripper design. There are many solutions available readily as discussed in the previous chapter. However, selection of such design can be demanding without some studies and design decisions. In this chapter, the proposed methodology for designing universal gripping solution will be discussed.

3.1 A proposal for Universal Gripping Methodology

As a consensus, the term universal means one for all. Therefore, universal gripper must mean that one gripper can grip all sorts of parts. Practically that is not possible because parts vary from sizes, weight, shapes, materials and all other ways. The application of this literature takes account the small-batch product manufacturing companies, where product's variety is extensive and newer products are introduced at a regular interval. Therefore, in context of this thesis, the term universal gripper means the availability of gripping system for the whole range of products within the work cell. Nevertheless, working with a single gripper will be the priority if it fits the window.

Over the years, many types of solutions are innovated to increase the universality of a gripping unit. Robot grippers are essential part of a robot work cell. Gripper selection itself is a challenging topic. It is always desirable to select the proper gripper from thousands of options to fit the application best. Pham & Yeo presented the governing factors for robot gripper selection in their article [32]. The governing factors are presented in the figure [41] below:

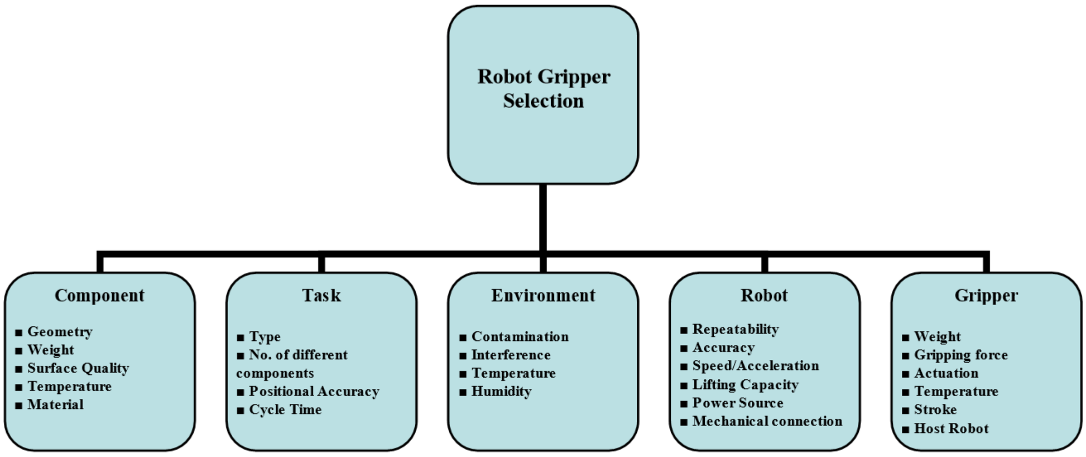


Figure 28. *Governing factor for gripper selection* [32][41]

From these factors the first four, Component, Task, Environment and Robot are dependent on the type of application. Therefore, only the gripper section is essential for this literature.

Azim, Lobov & Pastukhov [41] presented a methodology for gripper selection and therefore achieving the universal gripping mechanism for any application. From the article, the steps for achieving universal gripping solution are discussed below:

Step 1: Component study:

1. Study the whole set of components in detail to measure some important parameters from the study.
2. Measure the weight, temperature tolerance, applicable force range for the parts and decide the gripping surface area of the whole set. Applicable force range implies for the grip force the parts can handle and the required force to grip the parts securely while the robot is in operation.
3. Therefore, the outcome from this step is to divide the parts within groups with respect to the gripping surface area, both in shapes and sizes.

Step 2: Gripper Attribute Selection:

1. From the result of step one, the important specifications of the gripper/s can be decided.
2. Depending on the gripping surface area length, from minimum to maximum, the stroke of the gripper can be selected.
3. Considering the weight of the biggest and the smallest part, the required minimum and maximum force range of the gripper can be selected.

4. Then the remaining important selection like the required repeatability, gripping speed, gripper mount type and temperature rating can be selected according to the demand of the application.
5. These steps should be repeated for each group of components.

Step 3: Universal Gripping Method Selection:

After the selection of the gripper or grippers for the whole range of parts, the selection of universal gripping mechanism becomes easy. As discussed in section 2.6, the list of the universal gripping method is given below:

1. Finger dimensioning method
2. Finger changing mechanism
    a. Automatic finger changing method
    b. Manual finger changing method
3. Multiple gripper frame
4. Gripper changing method
    a. Automatic gripper changing method
    b. Manual gripper changing method
5. End of arm tooling method

The steps are illustrated in the below figure from the article "Methodology for implementing universal gripping solution for robot application" [41].

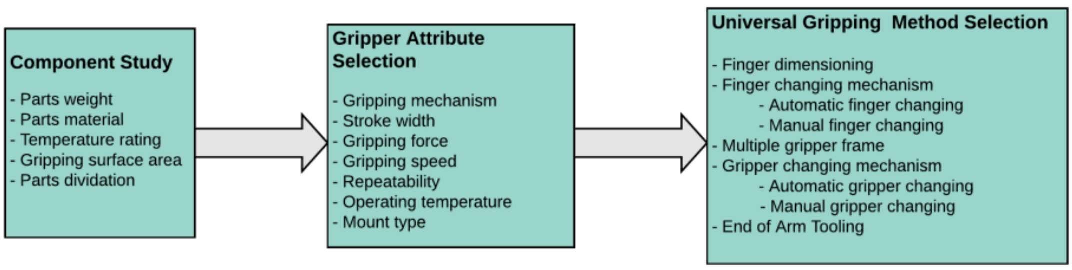


Figure 29. *Steps for achieving Universal gripping solution* [41]

Causey & Quinn in there article [37] presented several guidelines to increase the throughput and reliability of the universal gripping unit. Those important considerations are:

1. Notching the exterior of gripper fingers to make the fingers compact and not disturbing the adjacent part while gripping target parts
2. Minimizing the gripper weight to increase the payload of the robot
3. Avoiding tool changing system as it increases the cycle time
4. Grasping the parts securely and using encompassing grip if possible as that ensures security of the parts while gripped

5. Minimizing gripper finger length as it effects the force of the gripper and avoiding deflection of the fingers
6. Installing multiple grippers on a single wrist if possible as it increases throughout
7. Gripping multiple shaped parts with a single gripper if possible. It increases the payload and avoids the need for tool change thus saving costs and time
8. Designing the fingers such that parts align while gripper is closing the fingers.

4. IMPLEMENTATION

In this chapter, the main design decisions like the robot selection, input & output buffer selection, gripper selection and the experiments conducted to achieve the objective of the thesis are presented.

4.1 Robot Selection

Robot is the primary and most important part of a work cell. It is also the most expensive part of the work cell. The present-day robot market is growing very fast. There are few robot manufacturing companies providing innovative solutions throughout the years. ABB, Fanuc, Mitsubishi, Kuka, Kawasaki, Yaskawa, Nachi, Denso, Omron, Epson and Universal Robots are notable members of the family. From all the names, some are innovating solutions for a long time, yet some are very new names with some creative offering. With the advancement in sensor technologies, newer robots are programmed with built in safety features and collaborative in their behavior with the environment. Universal robot is one of them. They are a Denmark based company leading their way in collaborative robotics. According to Technavio [42], Universal Robots produce lightweight, flexible and easy to use robots. They also state that, these characteristics made them a versatile choice in many industry categories. Considering the work parts, cost effectiveness, flexibility and operation type, the UR5 model of Universal Robots was selected for the operation of soldering work cell. Until now, they produce three different robots, UR3, UR5, UR10 the numbers indicating the payload capacity of the robots.

UR5[1]

UR5 meaning the Universal Robot 5, has a 5 kg payload capacity. It is 6 degrees of freedom (DoF) robot arm with a reach of 850 mm. This robot weighs only a 20.6 kg for which it is very easy to transport from one place to another. This robot comes in a package with very minimal setup, a control box with input and output ports and a teach pendant which is used for programming the robot. The teach pendant uses a 12-inch touch screen Polyscope graphical user interface. The teach pendant offers an easy and intuitive programming environment. Therefore, the time required for programming the robot is very less. In addition, there is an online academy provided by the manufacturer, which simplifies the basic programming techniques by simulated tutorials. This online academy is interactive and the basic programming from the teach pendant can be done in few hours. The collaborative feature of the robot ensures the safety of the workers and therefore eliminates the need for a protective barrier caging of the work cell. [1]

Fig. 30[1] presents a Universal Robot.

Figure 30. *UR5 robot [1]*

4.2 Input & Output Buffer

The input and output buffer ensure the flow of the products in the work cell. For this use case, different type of solutions were proposed. From them, the conveyor belt system, chain system, stationary station are notable. Continuous belt system would have been a proper choice, as it ensures automatic feed to the robot. However, the parts in this case are needed to be properly oriented for the robot to pick up. Automatic orientation of the parts in the belt could be demanding as the parts are very lightweight and vary in sizes and shapes. Therefore, a stationary station was immediate solution.

For stationary station, there are different types of possibilities. As the parts are needed to be oriented properly and due to their lightweight characteristic, wooden indexing station was constructed specific to a single part by the company. The pilot indexing table is capable to feed 25 coils in a single batch. The indexing table is machined to have holes patterned to match the pin configuration of the specific coil. Therefore, part of the coils remain inside the indexing station. This configuration is advantageous to the system as the parts remain oriented in the buffer. However, there is a need to develop unique input buffer to each unique part.

---

[1] https://www.universal-robots.com/

The SMPS coils come in batches from the winding station. An operator transports this batch to the soldering station. The indexing station is then fixed in the white platform as can be seen in Fig. 31. The coils are then mounted on the indexing station by hand. The

Figure 31. *Indexing Station with coils mounted as an input buffer*

The output buffer is the place where the finished products are passed to the next station. As the parts are completed in batches, it was also selected to be stationary. In the output buffer, there is no requirement of orientation. Therefore, a simple SSI Schafer tray [43] was selected to be the output buffer by the company. Robot places all the parts uniformly in this tray and after the cycle is finished, the operator transports this to the next station. Fig. 32 presents an output buffer tray with soldered coils in it.

Figure 32. *SSI Schafer tray with soldered coil as an output buffer*

4.3 Robot Work Cell

As per discussion from Chapter 2 and the characteristics of the application, it is a logical choice to apply a robot centered work cell. The application involves soldering of small batches of product. The processing station in this work cell is soldering and fluxing station. These are stationary entities in the work cell. These stations will occupy a limited space in the work cell, which is within the reach of the robot. Therefore, the robot is not required any movement to reach the processing stations. The only moveable objects in the cell are the work pieces, which robot will transport from input buffer to the output buffer after the processing. Hence, robot centered work cell is an appropriate choice for this application, which will establish the workflow.

The proposed workflow of the cell is described below:

1. An operator will bring a batch of copper wounded coils from the winding station to the soldering station
2. The operator will load the indexing station on the input buffer according to the type of coil
3. Then the operator will fill up the indexing station with the coils one by one
4. The operator will turn on the soldering station, select the robot program from the archive for the specific coil type and start the program.
5. The robot will pick up the parts one by one and dip the part in the flux, wait for some time, dip it in the soldering wave and wait for some time, then place the part on the tray. The dipping procedure of coils in the soldering wave depends on the coil type. Some coils need fluxing and dipping in several cycles due to the placement of the pins.
6. The operator needs to fill up the indexing station before one cycle is completed.
7. The cycle is repeated until the batch is complete.
8. The robot stops operation according to the program and waits for the next batch.

4.4 Work part description

As discussed earlier in Chapter 1, 53 variants of SMPS transformer coils were delivered for studying and testing. These 53 variants represented every category the company produce according to the gripping perspective. They are all different parts with different sizes and several shapes. All the parts have plastic frame and metal pins usually facing downwards except few with exception in pin placement. The initial phase of the project started with study of this work parts. From all the types, some part types are demonstrated. The type description is according to the gripping perspective and shape.

Parts with rectangular shape & cylindrical core

These types of parts are square shaped. They stand on the vertical pins, which are dipped in the soldering wave. Some pictures of parts with this shape are provided below:

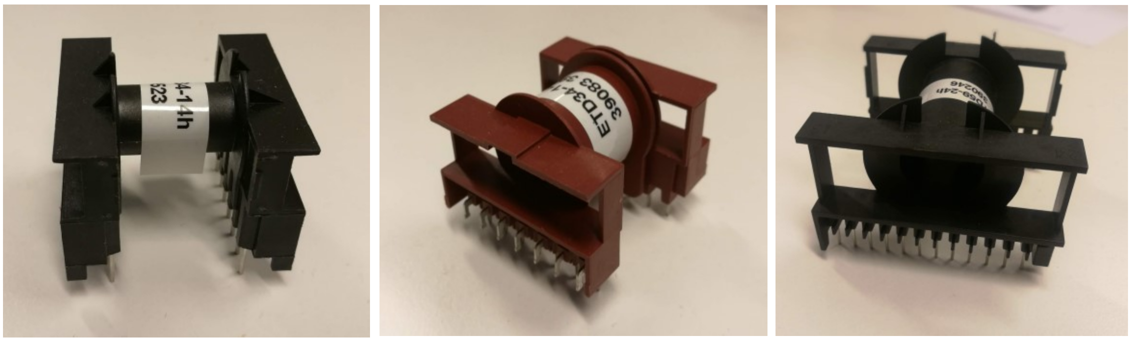


Figure 33. *Parts with square shapes & cylindrical core*

Parts with rectangular shape & rectangular core

There are few numbers in this group. Unlike the previous group, these parts have rectangular core shape. Some pictures are presented in figure 34.

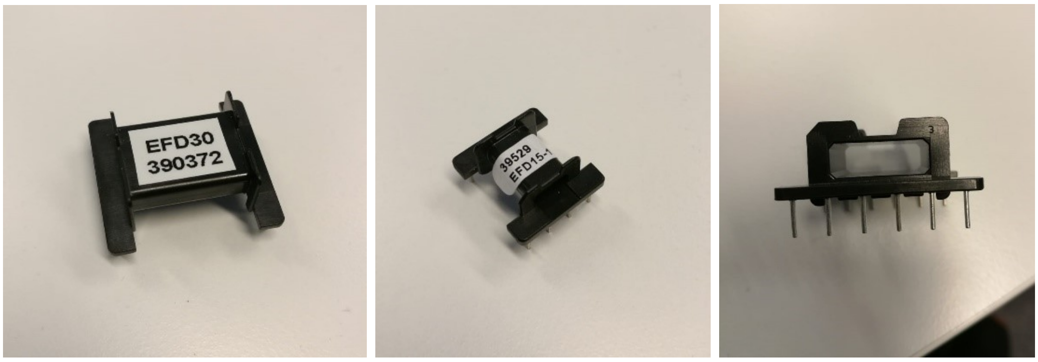


Figure 34. *Parts with rectangular shape & rectangular core*

Parts with circular shape & vertical core

From the gripping perspective, these parts are circular in shape and the core of the transformers are vertical. Like the previous types, these also stand on the pins, which requires soldering. Some picture of these types of parts are presented below:

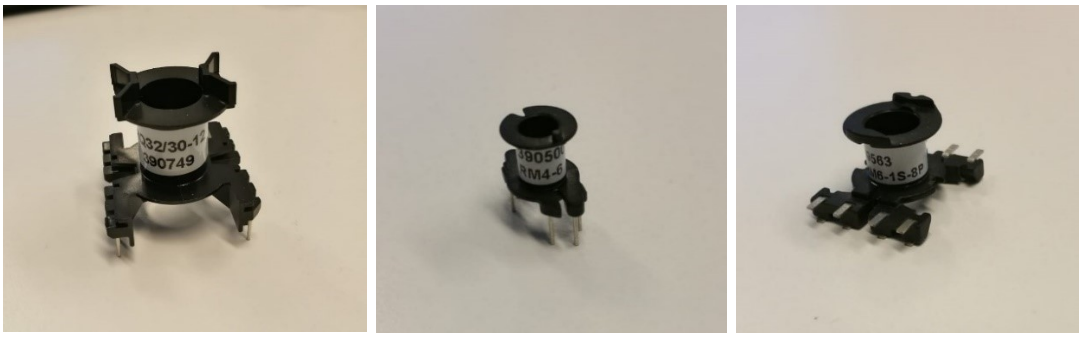


Figure 35. *Parts with circular shape & vertical core*

Parts with circular shape & horizontal core:

This type has only two members. These parts are small. Figure 36 includes some pictures of the parts.

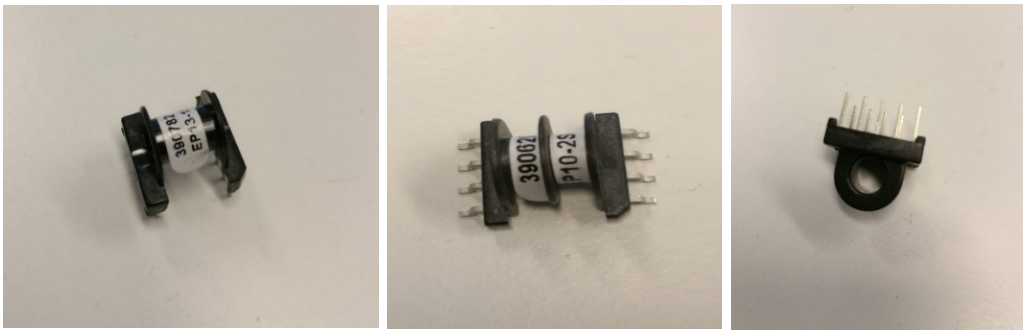


Figure 36. *Parts with circular shape & horizontal core*

After studying the parts according to the gripping surface, two major groups were created. 1) Parts with rectangular gripping and 2) Parts with circular gripping. Parts with rectangular shape & rectangular core and parts with circular shape & horizontal core were placed within the rectangular shaped group, as these parts can be gripped with the same gripper. Therefore, the parts of the first group can be gripped by the outer rectangular frame marked in red in figure 37. The parts of group 2 can be gripped in two ways. First, by the outer circular frame marked with red in figure 38, second, from inside the core marked with blue in figure 38.

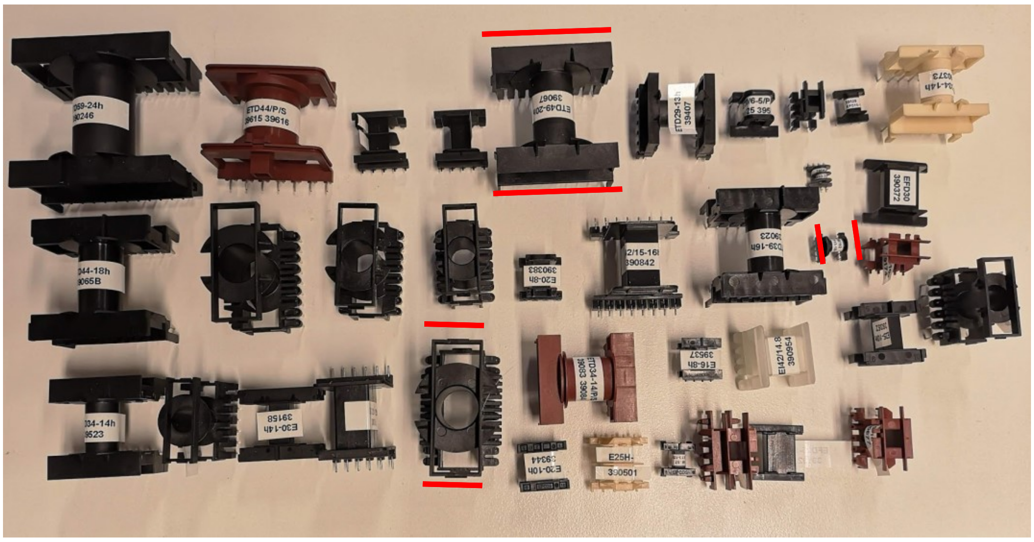


Figure 37. *Group 1: Parts with rectangular gripping*

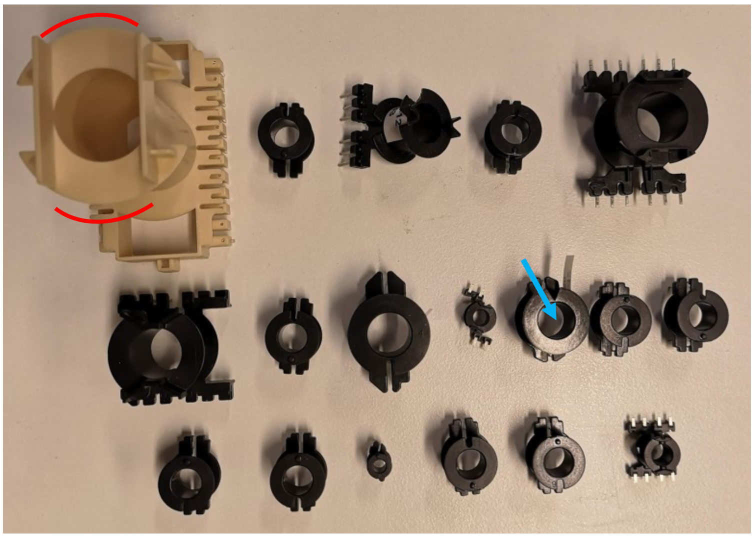


Figure 38. *Group 2: Parts with circular gripping*

After the gripping surface was decided, the other significant information about the parts were measured.

1. **Weight:** The weight of all the parts were measured. They varied between 0.02 to 0.1 Kg.
2. **Stroke:** The gripping surface area of all the parts were measured. The surface area of the smallest part was 7 mm and the biggest part was 66 mm.
3. **Material:** The part material is plastic, and it is common for all the parts.

The calculation led to some important decision regarding the specification selection for the gripper.

1. The stroke required for the gripper was 4-69 mm at least
2. It was decided that plastic fingers will be used for handling the parts.
3. The minimum gripping force required for the parts were calculated from 3.92 N to 19.6 N. The calculation was done by putting the weight of the parts to Eq. 2 presented in 2.5. The calculations are presented below:

   $$F = \frac{0.02 * 9.8}{2 * 0.1} * 4 = 3.92\ N\ (For\ the\ smallest\ part)$$

   $$F = \frac{0.1 * 9.8}{2 * 0.1} * 4 = 19.6\ N\ (For\ the\ biggest\ part)$$

   The gripping force was calculated considering 20 times more force than the part weight as suggested in the guide by gripper maker SMC [31].
   The coefficient of friction was selected 0.1. Some guidelines on selection of coefficient of friction can be found from the website [44]. Although for plastic to plastic, the coefficient of friction is given 0.3 [44], 0.1 was selected as the coefficient of friction to keep the safety margin and if the fingers were later replaced by metal fingers. The safety factor was calculated to be 4, as the robot will be moving heavily while the parts are gripped by the gripper.
4. The gripper control system can be either pneumatic or electric with two finger parallel gripper and three-finger gripper if we consider the inner gripping of the 2nd group.

4.5 Robot Gripper Selection

Following the previous step, all the required essential data was gathered for the gripper selection. From the data, a gripper named Robotiq 2f – 85 by the company Robotiq was selected for the application. The decision was taken based on some considerations. Those are listed below:

1. This gripper model is compatible with the robot UR5 and the company have integrated control of the gripper within the controller of the robot. So, that eliminates the time requirements for the programming of the gripper.
2. The stroke range of the gripper is 0 – 85 mm. As the requirement was 4 – 69 mm, it is more than enough for this application.
3. The gripping force range of this gripper is 20 – 235 N, which is a bit more than the required force. The applied force can ensure the security of the part while gripped. The extra force can be applied if the parts are not damaged while making the operation more secure. The parts were tested with the minimum force of 20N and all the parts survived the pressure in the initial test.

4. The gripper is an electric 2-finger angled gripper, which provides a good position resolution of 0.2 mm, which will be beneficial for the application while in operation with the smaller member of the part family. As it is an electric gripper, it provides good control of position and force by a unit of 1%.
5. The gripper fingers are removable and modified finger can be attached.

Therefore, the overall decision was easy to make, and it suited the application well. In Fig. 39 [45] the Robotiq 2f – 85 gripper is presented.

Figure 39. *Robotiq 2f – 85 electric gripper* [45]

4.6 Conducted Experiments to refine the approach

With the above selection of robot and the gripper, and the study of the parts, the process followed with several experiments. Following the proposed methodology for universal gripping in chapter 3, the first two steps were completed with the study of the parts and the gripper selection.

The experiments were conducted to find the proper gripping solution for all the parts and achieving universal gripping solution for the whole range. These experiments will be discussed in this section.

From the discussion of the work part description, it was specified that two surface types were needed to be gripped. Therefore, the experiments started to apply the finger dimensioning method as a universal gripping solution. There were both successful and failed experiments. The experiments and the approaches toward handling the problem are presented below.

4.6.1 Approach 1

Gripper Testing with Default Finger Set

The gripper came with a set of aluminum gripper fingers with rubber padding. Therefore, the testing was immediately started with the set. The gripper was tested with both rectangular and circular shaped parts. For convenience, the part group will be identified by their group number, 1 & 2. As discussed earlier, group 1 consists of rectangular parts and group 2 of circular parts.

The gripper was tested for both type of parts and some observations were noted. Those observations are listed below:

1. Group 1 parts did not face any problem while parallel gripping by the gripper. Although the silicon pads on the aluminum fingers were causing some problems while releasing the coils. The thin edges of the coils were remaining stick with the rubber pads.
2. Group 2 or the circular parts were not remaining uniform while gripped using the parallel gripping. The circular edges also remained stuck in the silica pads. Picking up the smaller members of this group were not possible due to the size and shape of the fingers.

4.6.2 Approach 2

The Toothpick Experiment

In this approach, an experiment was conducted to test the inner gripping of the group 2 circular parts as the group 1 parts were gripped successfully by parallel gripping. In this experiment, two toothpicks were attached with a scotch tape to the gripper fingers. With the toothpicks mounted, the gripper was tested for group 2 parts. Fig 40 presents the implementation of the idea.

While testing with this approach, some observations were noted. Those are listed below:

1. The inner grip was successful. The gripper could grip the circular parts from inside using the two toothpicks. It could even enter and pick up the smallest member of the group, which has a diameter of 4 mm only.

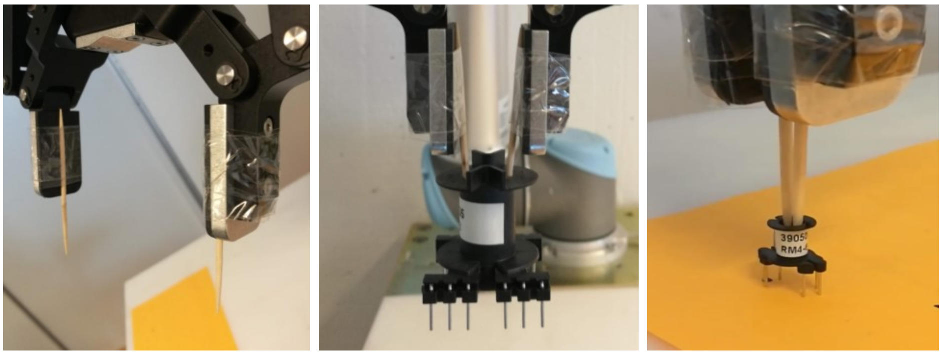


Figure 40. *The toothpick experiment*

4.6.3 Approach 3

3D Printed Toothpick Fingers

Considering the success of the toothpick experiment, the idea was extended. With the measurement of the gripper fingers, a 3D model using the SolidWorks software was developed mimicking the toothpick experiment finger configuration. The design was then printed with a 3D printing machine. The 3D printer could not print the thin toothpick shaped design. Fig. 41 shows the problem with the 3D printing.

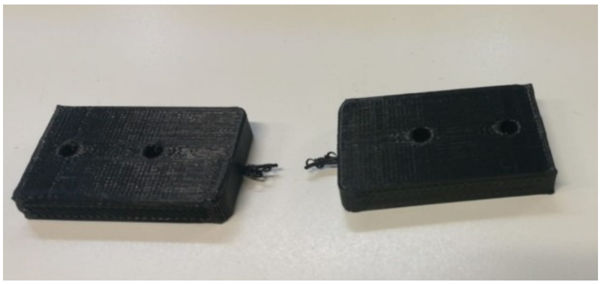


Figure 41. *1st 3D printed prototype*

Therefore, the design was modified with a hole at the bottom, instead of toothpick type design. Then, two toothpicks were entered through the hole as a temporary solution to test the prototype. The resulting finger looked like the figure below:

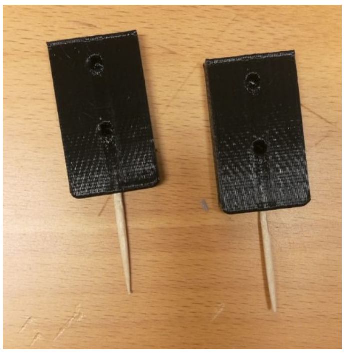


Figure 42. *The 2^{nd} 3D printed prototype*

This prototype was tested for both group of parts. In the process, some observations were noted. Those are listed below:

1. The inner grip was still a success. The finger could grip all the parts from the group 2 family.
2. The gripper fingers were facing problem gripping the rectangular group 1 parts. The toothpicks were touching the ground while reaching the parts, especially when gripping the smaller parts of the group 1 family. Therefore, the implementation needed some change in configuration, which led to Approach 4.

4.6.4 Approach 4

3D Printed Fingers with Rubber Coated Pins

In this approach, the 3D model was refined. The position of the hole was shifted to the z axis of the finger. The holes were placed slightly tilted so that the gripper does not need to change the orientation to 90 degrees. Then two thick toothpick shaped pin was modified by placing rubber grip on it. Eventually, those pins were glued inside the hole on the finger. The design looks like the figure below:

Figure 43. *The 3^{rd} 3D printed finger prototype*

These fingers were attached to the gripper. Then it was tested with all parts from group 1 & 2 family. From the experiment, there were some observations noted:

1. The rectangular parts were facing no problems as it was using only parallel grip.
2. The circular parts were gripped with the pins. The grip of this group was good although the pins needed to enter the center pint of the coils every time. Otherwise, the grip was not reliable. Furthermore, with time, the metal pins were being skewed with the force applied by the gripper. For the smallest part of this family, having diameter of 4 mm, the rubber-mounted pins could not enter the core of it. Therefore, this design was not feasible and reliable to implement, which led to approach 5.

4.6.5 Approach 5

New 3D Printed Gripper Finger with Notch

With the failure of the previous approach, the toothpick or inner gripping of the circular parts were discarded to continue with the finger dimensioning method. A fresh new design was developed using this method. The design was carried out with the thought of using the same side of the finger for both groups. It uses parallel grip for both categories. There is a notch placed to be able to grip the circular parts. For the parts of group 1, the two edges of the fingers were used as a parallel gripper. The notch did not play any role for the group 1 parts. It was only placed to produce the grip for the group 2 parts.

In the design process, the size of the notch placed an important role. The size of the notch will be so that, the biggest part can be gripped with a small portion of it entering the notch to provide the grip and the smallest part can be fit inside and the fingers can hold the part. In the process, it happened that for an increased size in few millimeters, the fingers could not hold the smallest part. Therefore, after many changes, the dimension was proper for the whole range of parts. The 3D model has been attached in Appendix A.

The design was printed using a 3D printer. The design looks like the figure below:

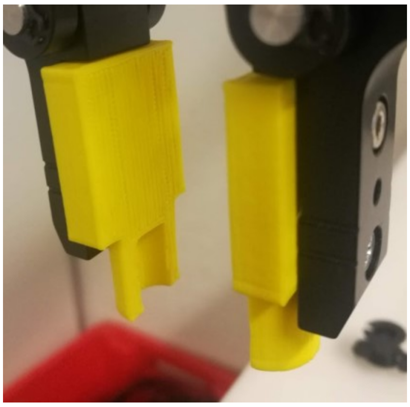


Figure 44. *The 4th 3D printed prototype of universal gripper finger*

This design was tested for all the parts. The experiment produced considerable results. It could grip all the parts from both group 1 and group 2 family with only one exception. The result of the experiment is discussed in the next chapter.

5. RESULT

In this chapter, the results from the latest designs are presented.

With the new 3D design, the gripper produced comprehensive results. The gripper gripped all the parts without facing any problem. Below pictures shows the ability of the gripper as a universal solution.

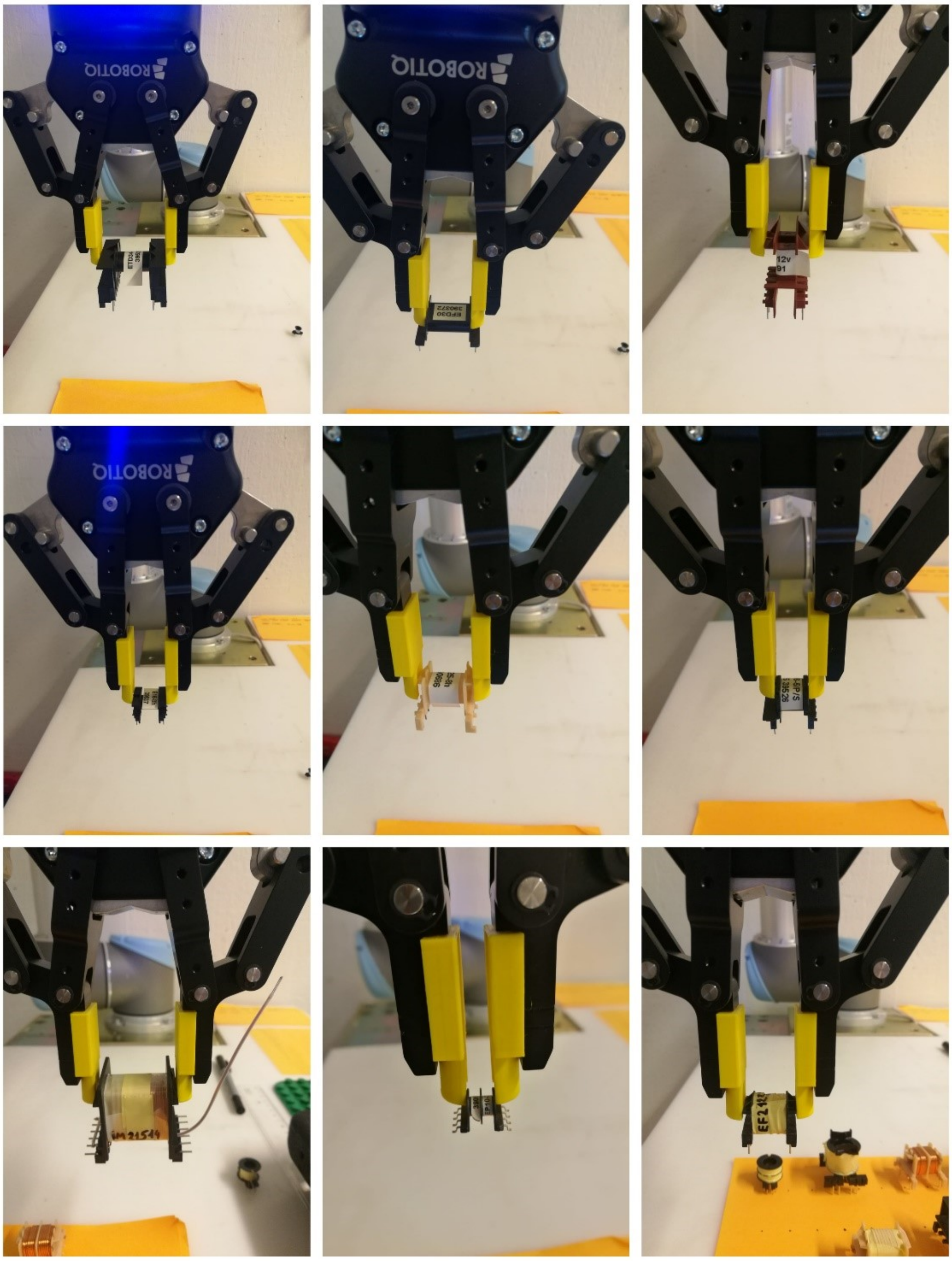


Figure 45. *3D printed finger prototype gripping the group 1 parts*

With proper orientation, the designed finger model can grip parts of different shapes and sizes from the range of parts.

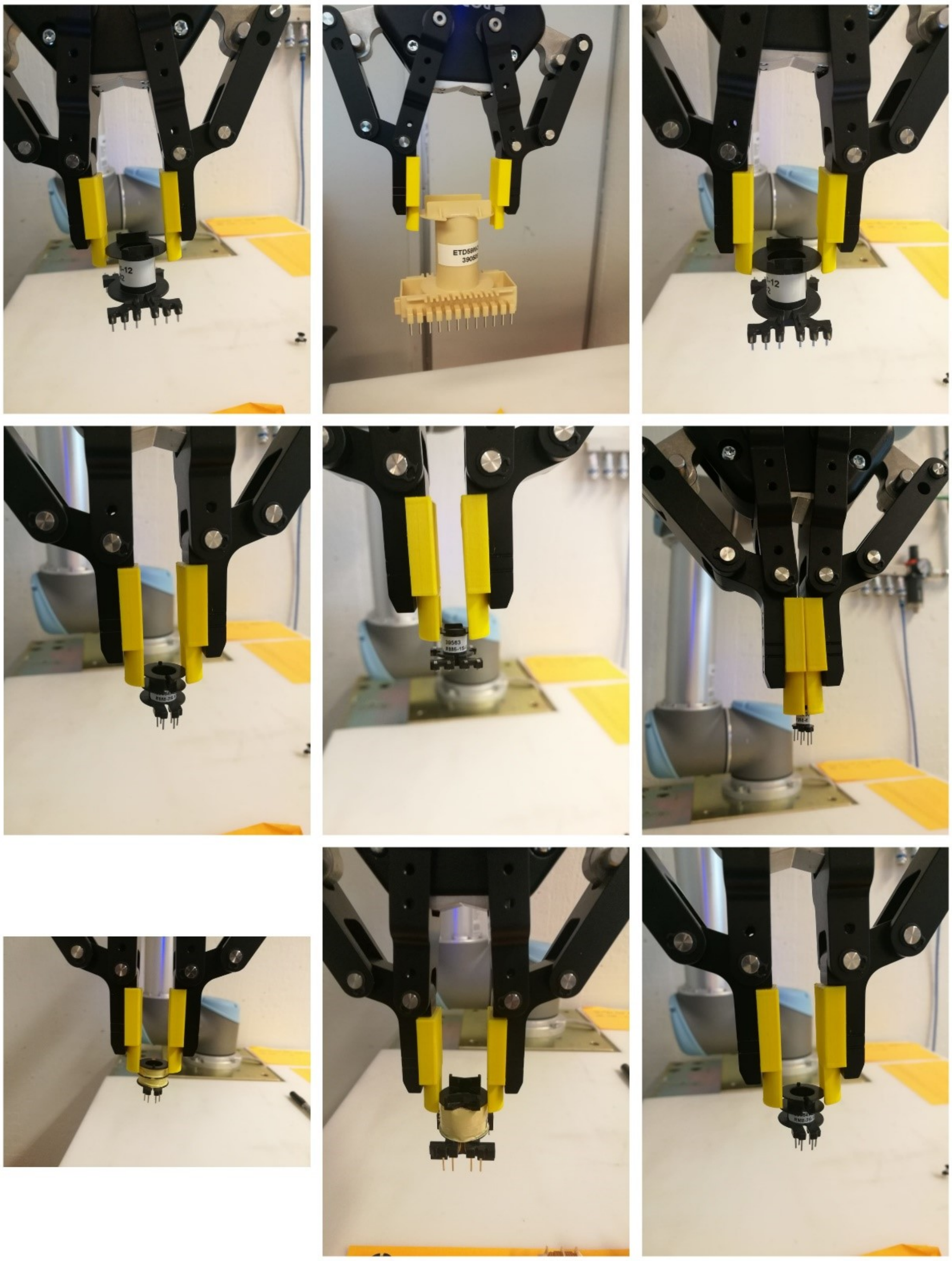


Figure 46. *3D printed finger prototype gripping the group 2 parts*

This configuration could grip all the variants of coils properly except one. This part is presented in below picture.

Figure 47. *Problematic part*

The grip of this part was challenging because of its shape. The grip was not so reliable and was loosely gripped and sometimes slipped from the gripper. This led to refine the universal gripper configuration to fit for all variants of parts.

The design was refined in Solidworks in a way that the width of the parallel gripping edges was increased. In addition, the size of the notch was slightly increased, so that the biggest part can be gripped more securely while the smallest part can be also hold tight between the two gripper-fingers. The schematic diagram of this design is provided in Appendix B. The new design compared to the old one is presented in below picture.

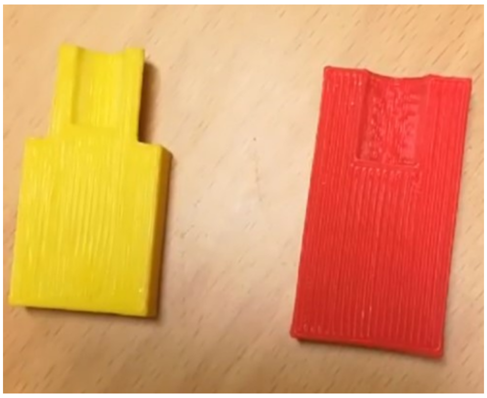


Figure 48. *The new and the final design*

The increased edges on both sides permitted to grip the problematic part with any one of the edges. With this design, it was possible to grip the part in two ways. The picture of the grips are presented in below pictures.

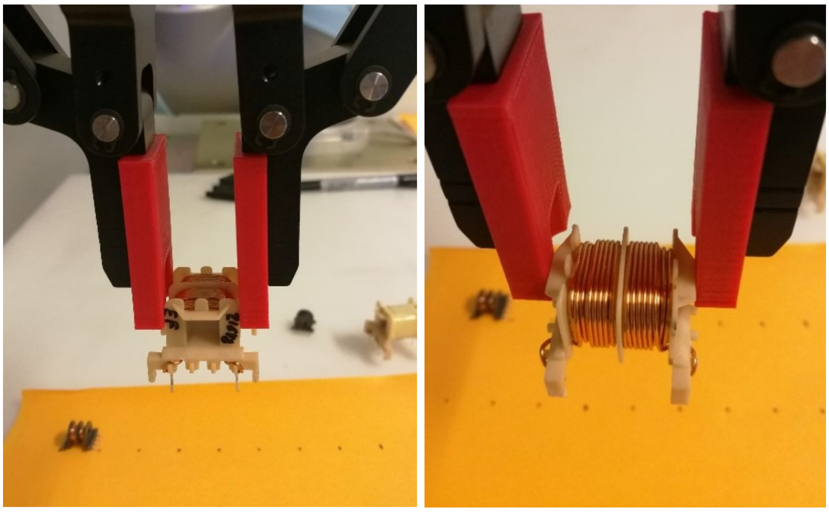


Figure 49. *Gripping the problematic part in two ways with new design*

This new design grips all the parts the same way the previous one gripped including the problematic part. Thus, making it the desired and final design for the universal gripping solution.

This gripper configuration made using the finger dimensioning method achieved the objective of the thesis with some positive endnotes. Those are listed below:

1. The finger dimension method achieved the universal gripping system for the whole range of parts used for the application of this thesis.
2. The fingers are easy to install.
3. It eliminated the need for a three-finger gripper, thus discarded the need for tool changing.
4. Using this method, the gripper does not decrease the payload of the robot, as the 3D printed fingers are very lightweight.
5. It minimized the cycle time of the operation thus increasing the overall throughput and efficiency of the work cell.
6. It minimized the overall cost of the system by not using extra hardware.
7. The fingers can be modified to fit any parallel gripper with slight changes in the 3D model.
8. The fingers are easy to install and saves the operator from extra maintenance of multiple grippers thus less downtime.
9. The fingers can be printed easily with 3D printer in very short time if it wears from excessive use.
10. The grip of the fingers with the applied force is secured. The selected force of the gripper was in between 20-30 N. The experiments were conducted with the robot in 100% acceleration and the gripping speed was kept close to 100%. The gripper gripped the parts securely without dropping a single time during the operations.

6. CONCLUSION

In this chapter the conclusion of this work is discussed. The learnings, success and failures are included in the first part of the conclusion. Future work can always modify and better the solution. The scope for future work is also discussed in the next part.

6.1 Conclusion of Implementation & Result

In a robot operated production, the challenges increase if the products are manufactured in small batches and the product variant is large. For this thesis, the problem is similar. At the initial phase, there were two major objectives of this thesis. The first one was to develop gripping mechanism for all the part variants and the next objective was to design a universal gripping mechanism for the range of products. Research was carried out on gripping mechanisms, common form of grippers, unorthodox gripping systems, universal gripping methods. The findings are documented on the second chapter. Through the course of this project, a universal gripping methodology was developed based on the experience and the findings from the previous work done on the topic. At first, the ideas emerged from the brainstorming and research were complicated and demanding. But at last, a simple and efficient design was developed. This design features numerous positive characteristics that ticks both the objectives of this thesis. The process for achieving this result is documented in the fourth and fifth chapter. Although the design fulfills the requirements of the project, still there are scope for betterment.

6.2 Future work

In the soldering work cell, an operator needs to be present to orient the parts in the indexing station before each cycle. Automating this part of the assembly can save a lot of time and manpower. This calls for more research work and time. The quality of the solder on the coils can also be automated with the help of machine vision system. If the operator intervention can be minimized, the efficiency of the work cell can be significantly increased.

With the machine vision system, the grip can be improved, and the idea of part specific indexing station can be also changed to a universal input buffer for all the parts.

In this thesis, the concern was toward the small batch, heavy variation product manufacturing companies. If the product variant is less and the batch size is substantial, then one can consider the relatively cheaper fixed automated stations supplied by many automation supplier companies. However, robot adds the flexibility to be used in other operations. Therefore, robot based solution can be beneficial rather than fixed automated stations.

REFERENCES

[1] B. Siciliano and O. Khatib, *Springer handbook of robotics*. Springer, 2016.

[2] "The First Industrial Robot (1954 – 1961) : HistoryofInformation.com." [Online]. Available: http://www.historyofinformation.com/expanded.php?id=4071. [Accessed: 09-Nov-2018].

[3] "Industrial: Robotics Outlook 2025 | Loup Ventures." [Online]. Available: https://loupventures.com/industrial-robotics-outlook-2025/. [Accessed: 09-Nov-2018].

[4] "10 robotic manufacturing systems." [Online]. Available: https://www.slideshare.net/ganeshmrgn/10-robotic-manufacturing-systems. [Accessed: 12-Nov-2018].

[5] A. O. Andrisano, F. Leali, M. Pellicciari, F. Pini, A. Vergnano, and F. Pini, "Integrated Design of Robotic Workcells for High Quality Machining Article Information," 2011.

[6] M. Bdiwi, M. Breitfeld, and M. Putz, "Unique Platform for Observing/Evaluating Various Levels of Interaction between Human and Industrial Robot," in *HRI '17 Proceedings of the Companion of the 2017 ACM/IEEE International Conference on Human-Robot Interaction*, 2017, pp. 405–405.

[7] L. Westerlund, *The extended arm of man: a history of industrial robot*. Informationsförlaget, 2000.

[8] V. D. Hunt, *Industrial robotics handbook*. Industrial Press Inc., 1983.

[9] "International Federation of Robotics." [Online]. Available: https://www.ifr.org/uploads/media/History_of_Industrial_Robots_online_brochure_by_IFR_2012.pdf. [Accessed: 20-Nov-2018].

[10] "Robot Configurations." [Online]. Available: http://my.ilstu.edu/~kldevin/Introduction_to_robotics2/mobile_pages/Introduction_to_robotics7.html. [Accessed: 03-May-2019].

[11] "Industrial grippers: History and new innovation | Machine Design." [Online]. Available: https://www.machinedesign.com/motion-control/industrial-grippers-history-and-new-innovation. [Accessed: 03-Dec-2018].

[12] R. Bostelman and J. Falco, "Survey of Industrial Manipulation Technologies for Autonomous Assembly Applications NIST-Internal Report #7844," 2012.

[13] "What are pneumatic grippers?" [Online]. Available: https://www.pneumatictips.com/what-are-pneumatic-grippers/. [Accessed: 04-Dec-2018].

[14] "Electric Gripper - Air Gripper Wholesale Supplier from Chennai." [Online]. Available: https://www.indiamart.com/suranapneumatics/electric-gripper.html. [Accessed: 24-Jan-2019].

[15] "Weblet Importer." [Online]. Available: http://www.millsom.com.au/products/vacuum-components/special-grippers/sgm. [Accessed: 24-Jan-2019].

[16] "FIPA vacuum products for the packaging industry." [Online]. Available: https://www.fipa.com/en_GB/flow/2490822-application-examples-packaging?flow=e1s1. [Accessed: 24-Jan-2019].

[17] "How Do Fingers on the 2-Finger 85 Adaptive Gripper Work?" [Online]. Available: https://blog.robotiq.com/bid/55922/How-Do-Fingers-on-the-2-Finger-Adaptive-Robot-Gripper-Work. [Accessed: 24-Jan-2019].

[18] "MultiChoiceGripper | Festo Corporate." [Online]. Available: https://www.festo.com/group/en/cms/10221.htm. [Accessed: 24-Jan-2019].

[19] K. Tai *et al.*, "State of the Art Robotic Grippers and Applications," *Robotics*, vol. 5, no. 2, p. 11, Jun. 2016.

[20] R. B. Kelley, J. R. Birk, H. A. S. Martins, and R. Tella, "A robot system which acquires cylindrical workpieces from bins," *IEEE Trans. Syst. Man. Cybern.*, vol. 12, no. 2, pp. 204–213, 1982.

[21] "The difference between robotic grippers with parallel, three-finger, and angled designs." [Online]. Available: https://www.machinedesign.com/robotics/difference-between-robotic-grippers-parallel-three-finger-and-angled-designs. [Accessed: 20-Jan-2019].

[22] "A history of gripping and gripper technologies and the available options for today's engineer." [Online]. Available: https://www.machinedesign.com/robotics/history-gripping-and-gripper-technologies-and-available-options-todays-engineer. [Accessed: 19-Jan-2019].

[23] "PAG-E Parallel Gripper Easy - Grippers - Mouldshop." [Online]. Available: http://mouldshop.co.uk/products/500011-grippers/500099-pag-e-parallel-gripper-easy/. [Accessed: 20-Jan-2019].

[24] F. R. E. Crossley and F. G. Umholtz, "Design for a three-fingered hand," *Mech. Mach. Theory*, vol. 12, no. 1, pp. 85–93, 1977.

[25] "Electric gripper T type (three fingers type) - Industrial robots | Yamaha Motor Co., Ltd." [Online]. Available: https://global.yamaha-motor.com/business/robot/lineup/yrg/t/index.html. [Accessed: 20-Jan-2019].

[26] "Angular Gripper - P5GA Series (economy) | Parker NA." [Online]. Available: http://ph.parker.com/us/en/angular-gripper-p5ga-pdn. [Accessed: 20-Jan-2019].

[27] "FlexShapeGripper | Festo Corporate." [Online]. Available: https://www.festo.com/group/en/cms/10217.htm. [Accessed: 20-Jan-2019].

[28] E. Brown *et al.*, “Universal robotic gripper based on the jamming of granular material.”

[29] “Vacuum Technology for Efficient Processes - Schmalz.” [Online]. Available: https://www.schmalz.com/en/. [Accessed: 20-Jan-2019].

[30] “Robotic End Effectors - Payload vs Grip Force.” [Online]. Available: https://blog.robotiq.com/bid/69524/Robotic-End-Effectors-Payload-vs-Grip-Force. [Accessed: 17-Dec-2018].

[31] “Electric Grippers.” [Online]. Available: http://smc138.valuehost.ru/c5/leh.pdf. [Accessed: 17-Dec-2018].

[32] D. T. Pham and S. H. Yeo, “Strategies for gripper design and selection in robotic assembly,” *Int. J. Prod. Res.*, vol. 29, no. 2, pp. 303–316, 1991.

[33] C. Johansson, N. Mårtensson, and G. Sohlenius, “Grippers, tools and fixtures for flexible automated assembling,” *CIRP Ann. Technol.*, vol. 34, no. 1, pp. 21–24, 1985.

[34] “How to replace the finger gears on the 3-Finger Gripper — DoF.” [Online]. Available: https://dof.robotiq.com/discussion/48/how-to-replace-the-finger-gears-on-the-3-finger-gripper. [Accessed: 27-Apr-2019].

[35] “Changing.” [Online]. Available: https://schunk.com/de_en/gripping-systems/category/gripping-systems/robot-accessories/changing/. [Accessed: 17-Dec-2018].

[36] “Products - Manual Tool Changer for Universal Robots - Millibar.” [Online]. Available: https://www.millibar.com/manual-tool-changer/. [Accessed: 17-Dec-2018].

[37] G. Causey and R. Quinn, “Gripper design guidelines for modular manufacturing,” 1998, pp. 1453–1458 vol.2.

[38] “Pneumatic gripper / parallel / 2-jaw / compact - RVK - SCHUNK - Videos.” [Online]. Available: http://www.directindustry.com/prod/schunk/product-12463-1585380.html. [Accessed: 24-Jan-2019].

[39] “Tooling – End of Arm Tooling, Inc.” [Online]. Available: https://eoat.net/tooling/. [Accessed: 17-Dec-2018].

[40] “Octopus-inspired robotic gripper handles delicate produce | ProFood World.” [Online]. Available: https://www.profoodworld.com/articles/octopus-inspired-robotic-gripper-handles-delicate-produce. [Accessed: 03-May-2019].

[41] M. S. Azim, A. Lobov, and A. Pastukhov, “Methodology for implementing Universal Gripping Solution for Robot Application,” to be published in *Proc. Est. Acad. Sci.*, 2019.

[42] “Top 21 Industrial Robotics Companies in 2018 | Global Industrial Robotics Market.” [Online]. Available: https://www.technavio.com/blog/top-21-

companies-in-the-industrial-robotics-market. [Accessed: 14-Nov-2018].

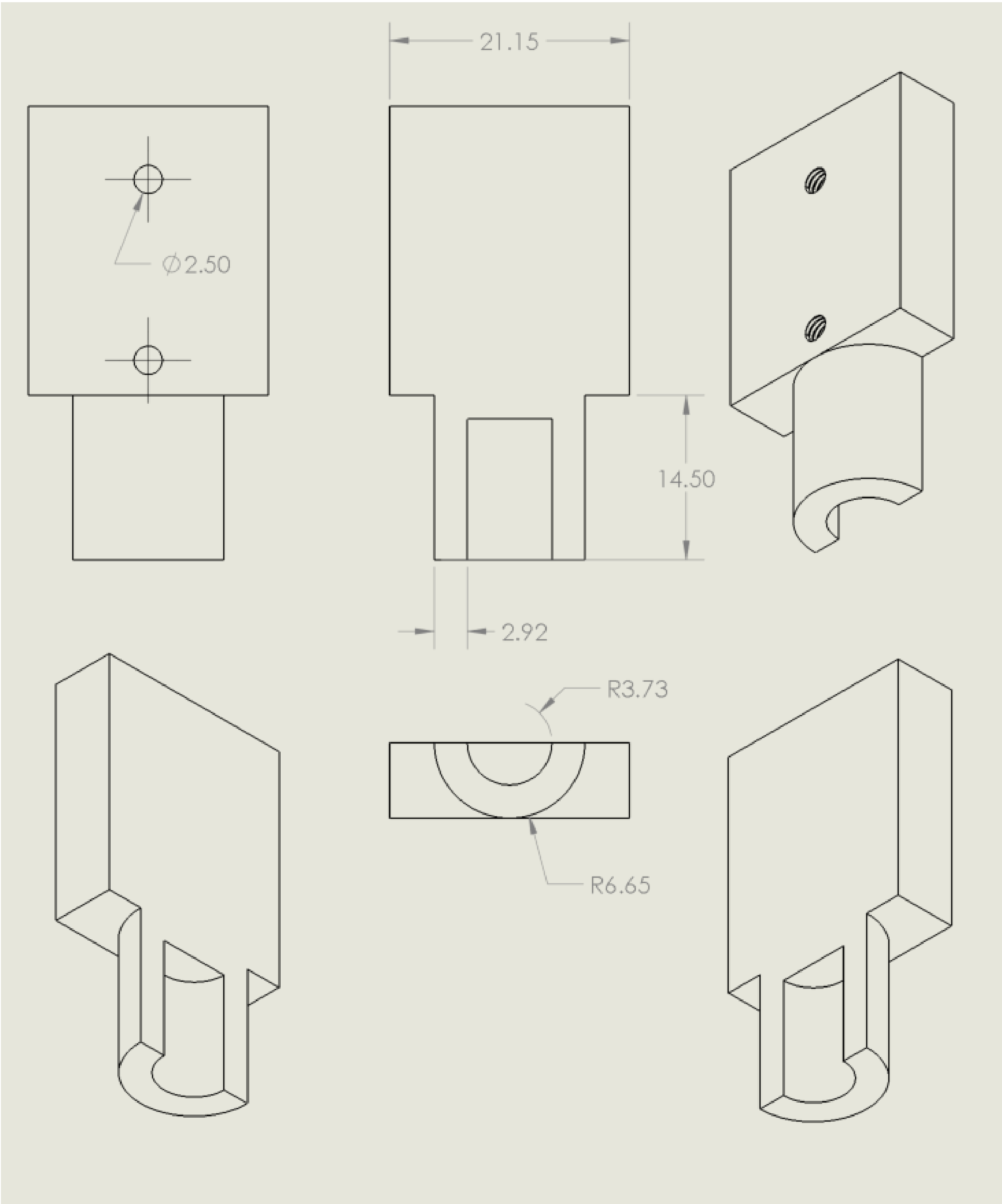
[43] “Container systems | SSI SCHAEFER.” [Online]. Available: https://www.ssi-schaefer.com/en-gb/products/storage/small-load-carriers/containers-totes-trays-and-bins. [Accessed: 24-Jan-2019].

[44] “Coefficient of friction, Rolling resistance, Air resistance, Aerodynamics.” [Online]. Available: http://www.tribology-abc.com/abc/cof.htm. [Accessed: 17-Dec-2018].

[45] “Robotiq 2-Finger 85mm Adaptive Robot Gripper for Universal Robots (AGC-UR-KIT-002) - Thinkbot Solutions.” [Online]. Available: https://www.thinkbotsolutions.com/shop/robotiq-2-finger-85. [Accessed: 24-Jan-2019].

APPENDIX A – SCHEMATIC DIAGRAM OF UVERSAL GRIPPER FINGER

All the measurements are in millimeters (mm)



APPENDIX B – SCHEMATIC DIAGRAM OF MODIFIED GRIPPER FINGER

All the measurements are in millimeters (mm)